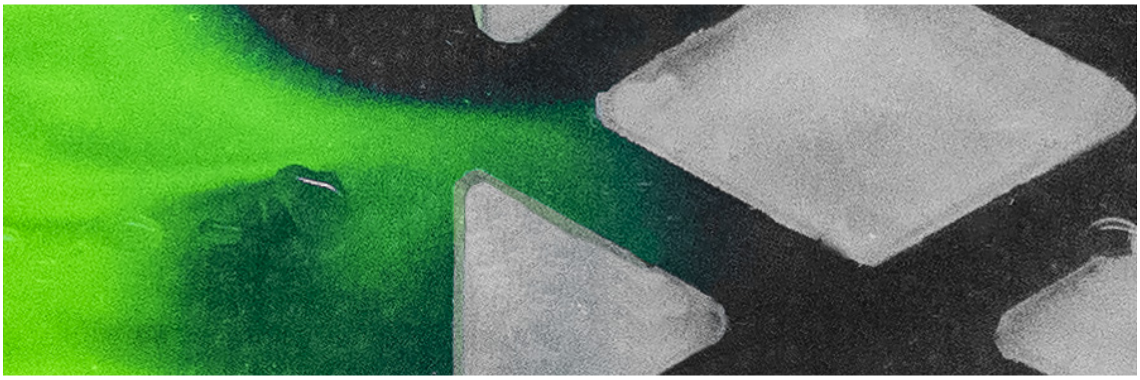
Discriminatory transient mass transfer through reticulated network geometries

a mechanism for integrating functionalities in the building envelope



David Nils-Gunnar Andréen

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VEIV, UCL Institute for Environmental Design and Engineering
The Bartlett, UCL

Declaration

I, David Andréen confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

In this thesis it is demonstrated how mass transfer can be induced within a network of reticulated channels through turbulent mixing, and how this mechanism can be applied as an integrated functional structure in a building envelope. The research is based on suggestions in literature that there are transient modes of mass transfer which are active in termite mounds of the species *Macrotermes michaelseni* and which do not rely on steady or cross flows: is the interaction of transient air flows, induced or natural, and the geometry found in the mounds – a complex reticulated network of tunnels with variable dimensions – conducive to controlled mass transfer? My original contribution is to show that such mass transfer is possible, to demonstrate the ways which geometry and input flow interact to create turbulent mixing, and to demonstrate how these parameters may be useful to control the flow within and across building elements.

The research method is structured around a series of experiments where various geometries, based on the egress complex of termite mounds, are exposed to transient fluid flows, either a controlled, low amplitude oscillation or external turbulent flow. The resulting mass transfer is measured using tracer gas measurements and visualisations using planar laser and/or fluorescent dye. It is found that the oscillations in certain conditions, which involve a combination of geometry and oscillation properties, lead to the emergence of large scale turbulent convection which can increase the mass transfer rates with up to two orders of magnitude over an unperturbed system.

It is concluded that such mechanisms are potentially useful to control the flows of heat and moisture within buildings and across building envelopes. The particular properties of the described flows can complement conventional steady flows and expands the repertoire available to the building designer, enabling new types of boundaries and functional integration in the building envelope.

Acknowledgements

This doctoral thesis is the outcome of a journey started in 2008, when I was invited to attend the Industrialised, Intelligent, Integrated Construction conference at Loughborough University and was first introduced to the Namibian termite mounds as models for construction scale additive manufacturing. During this journey I have been privileged to collaborate with a great number of people, and while I cannot mention them all here, there are a number of persons and organisations to whom I would like to extend my particular gratitude.

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Throughout the project, I have had the pleasure of collaborating with Rupert Soar, who was the first person to explore the potential implications of termite mound studies on the construction industry, and linking it to additive manufacturing. From our first contact to an ongoing sharing of ideas, you have been a great help and inspiration. His input has been crucial for some of the work undertaken in this thesis, especially the experiments described in chapter four. Through Dr. Soar I have been able to participate in an international collaborative research project funded through the Human Frontiers Science Program, which has allowed me to study the termite mounds in their natural environment and meet researchers in disciplines spanning from applied mathematics to biology. Among them is Scott Turner, who is the physiologist behind the first suggestions that transient flows play a critical role in the termite mound physiology, and who has helped me gain insight into the world of physiology in a way which few architects get the opportunity to do. I would also like to thank Hunter King, Sam Ocko, Paul Bardunias, Pallavi Sharma, Sanjay Sane, and Eugene Marais, all of whom have at some point helped me develop my thoughts and push my project forward, directly or indirectly.

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Chapter 1

Introduction

I want to stay as close to the edge as I can without going over. Out on the edge you can see all kinds of things you can't see from the center.

– Kurt Vonnegut, Jr[1]

1.1 The functional nature of form and complexity

The primary function of buildings is to create differentiation and separation, both conceptual and physical. The building envelope is the part of the building that to the greatest extent, and often exclusively, defines this differentiation, whether it is physical – e.g. between hot and cold, calm and windy, safe and dangerous – or conceptual – e.g. sense of place and identity, legal belonging, symbolic and cultural meaning.

With few exceptions, the boundaries that are created in terms of the physical and the conceptual are different in that the conceptual boundaries are more fluid, being both more diffuse and less continuous, often shifting depending on the perspective of the observer, whereas the physical boundaries are absolute and provide clear, direct changes in quantifiable euclidean space.

This thesis is built around a proposal that this distinction is artificial, and that the contemporary engineering philosophy around a building envelope is posed to enter a transition phase where the binary absolute of the building envelope can be replaced by a fluidity which has the potential

[1](Vonnegut 1952)

to deliver a much higher level of integrated functionality. The change[2] is made possible by the emergence of digital design and fabrication processes, and the hypothesised mediating boundary condition is largely reminiscent of the homoeostatic boundaries defining organism in biological systems.

Whereas typical building boundaries are based on the fundamental principle of achieving maximum separation – the ideal being minimal air or heat flux, while using external electric energy to maintain a differentiated internal climate – boundaries in nature rely on functional membranes, exploiting local gradients in energy and molecular concentrations to drive differentiating processes. Most evident are such boundaries within organisms, e.g. cell membranes, organelles, or organs, but we also see them at external or macro levels where organisms interact with their surroundings: from the geometry of coral reefs[3] or barnacle colonies which help them funnel nutrients and food towards themselves, to the nests of burrowing animals, or indeed the termite mounds which are discussed in great detail later in this thesis. This physiological approach is not static but dynamic, relying on finely tuned processes and structures in order to convert potential to work and is as such inherently flexible and adaptive.

From an architectural perspective such a model would imply that the distinction between the envelope (which typically is intended to limit flows between building and surrounding) and the work performed by machines powered by external energy (heating, ventilation, air conditioning) is replaced by an integrated view of the building structure where flows (of air, heat, water) are actively and dynamically manipulated through the interaction of the building geometry and material, surrounding energy flows and gradients, and electric input. By leaving the binary separation of inside and outside, energy can be saved by prioritizing the use of ambient energy (wind, sun, heat) to drive these flows when this is available and only relying on electric energy when necessary, and by applying the energy only in the time and place where the effect is greatest.

In biology, the processes that define such a dynamic boundary are reliant on structure and geometry: they differentiate space to create steep gradients and manipulate flows in useful manners. This differentiation happens at small scales as well as large, and in complex 3-dimensional space as opposed to conventional envelope engineering which is constrained to perform in 1 or 2 dimensions. It is imperatively adapted to micro-context and universally applicable generalisations are rare if present at all. The ability to fabricate such structures has been beyond the scope of contemporary construction processes until very recently, when computer aided manufacturing (CAM) emerged as a viable alternative. Today, we are seeing a rapid movement towards construction scale implementations of such processes (Soar and Andreen 2012), and while the cost and difficulties are still significant, it is likely only a matter of time before mass-customisation and complex geometries at the scales required are within reach for architectural engineering.

In order to explore what such a boundary may be and how it could be achieved and perform from an engineering perspective, this thesis is investigating the mounds of *Macrotermes michaelseni*, a Sub-Saharan termite species that build impressive mud structures above their nests which are believed to play an important role in the respiratory gas exchange of the termite and symbiotic fungus colony. It has been speculated in literature that the mass transfer mechanisms involved are transient in nature rather than relying on steady state flows, and that this carries with it significant

[2] A change to recent practice, but which in many ways represents a return to vernacular strategies of building function but without the inefficiencies associated with such buildings.

[3] The relationships of coral morphology, transient flows and mass transfer is explored in a fascinating article by Reidenbach et al. (2012).

benefits in reliability and function (Turner 2001; Turner and Soar 2008).

Within the mound, the highly intricate network of tunnels appear to interact with transient winds – turbulence, eddies, fluctuating velocities and directions – in ways which create flows of matter and energy in unexpected ways. This thesis investigates some of these mechanisms, building up a model for how they can be created and controlled, and proposes ways in which they can be used in a building envelope or structure to create the type of active and dynamic boundary described above.

1.2 Problem statement

The increasing ability to manage geometric complexity in architectural contexts, driven mostly by the development of digital tools in design and fabrication, is opening up new possibilities for design. The research question addressed in this thesis relates to one way in which these possibilities can be exploited for functional use: How can transient and non-laminar flows be controlled and generated within a building in order to manipulate the building climate to promote increased human comfort and reduced energy footprint? Specifically, the thesis will explore the interaction of transient (oscillating and turbulent) air-flows with certain geometries modelled on termite mounds, and test the hypothesis that these geometries interact with natural or induced transient flows in ways which promote controlled mass transfer across the geometry. There are currently no models that predict that a net mass transfer would arise from such conditions, and effectively ventilate a "dead zone" (Neeper 2001; Braun et al. 2009), but they have been loosely hypothesised in literature (Turner and Soar 2008). The suggestion here is that such flows can be generated in a controlled manner within the structural elements of a building, and that this allows for selective transfer of heat or moisture through convection in and out of buffer materials integrated into the building envelope or other constructional elements. The advantage of such a capacity would be to use spatial and temporal variation of (primarily external) temperatures or humidity levels to affect the internal building climate in favourable ways, thus reducing the need for electricity or fuel. The contribution of this thesis is to show how these flows can be generated and controlled, and to describe the principles through which they could be applied in architectural designs.

1.2.1 Transient heat and mass transfer for internal climate regulation

Transient and turbulent mechanisms are largely disregarded (or actively avoided) in building engineering because they are considered too difficult to quantify and predict, and because they can lead to reduced linear efficiency in conventional application, primarily due to increased friction in steady flows (*Handbook, ASHRAE Fundamentals* 1997). However, they are frequently exploited by organisms in physiological functions, such as is the case with *Macrotermes michaelseni* termites, which build large mounds thought to use transient flows to mediate relationships between the colony and the surrounding environment.

In building practice, both current and historic, much effort is put into developing passive or natural means of regulating the building climate. As the ambition is to reduce the energy consumption, these efforts are concerned with intelligent and selective heat and mass transfer between the building and its environment, as well as within the building. A building's ideal internal climate, in this case primarily its temperature (although similar logic applies to moisture), is typically different from the surrounding's. The conventional way of achieving this difference is by creating a barrier between inside and outside, thus reducing flows of heat, and by producing warmth internally by external energy input (electricity, fuel), or by actively pumping out the heat (using electricity).

An alternative approach is to achieve the same effect by utilising the variability of the external conditions. Temperature varies over time (e.g. diurnal cycles, weather) and space (e.g. solar gains), and by increasing the flows of heat during favourable times and to/from favourable locations, the internal climate can be kept closer to the ideal, through the intelligent exploitation of ambient energy. This effect can be strengthened if the heat or coolth can be efficiently stored over time (which allows for temporal displacement in addition to spatial), for example by storing night time coolth and releasing it into the building during the hottest hours. Many systems, both vernacular and contemporary, exploit such mechanisms, and are described in the literature review.

To maximise the effectiveness of such systems, it is important on the one hand to ensure a high thermal storage capacity, and on the other to control the flow of heat between the storage medium, the building exterior and the building interior. The first parameter is the focus of much current research, see e.g. Zhang et al. (2007) or Padfield and Jensen (2011), and many high performance materials have been developed. The second parameter, the control and magnitude of transfer rates, is the main focus of this research, and is important because it allows for a maximum utilisation of ambient resources when conditions are most favourable. This is particularly important with high performance materials with large heat capacity in limited mass, where the heat flux is likely to be a performance bottleneck (Zhang et al. 2007).

In current building practice, as well as most state of the art research, steady bulk flows are almost exclusively exploited to achieve this mass and heat transfer when high transfer rates are desirable and diffusion/conduction is too slow. Such flows are well understood and easy to control, but they suffer from a number of drawbacks. Bulk flows rely on cross flow: continuous streams of air or water from an inlet point to an outlet, between which the flow is static and uniform, and it can not be selectively turned on or off without mechanical valves. The geometric complexity, which is important for maximising surface area and therefore heat flow between solids and air, is limited by this continuous flow condition, and also because of flow resistance considerations. Flow resistance increases exponentially with both shrinking radii and increased tortuosity − large diameter ventilation pipes are required to keep noise and energy consumption low. In combination with the laminar nature of such flows and the associated formation of a significant boundary layer, which limits the interchange of mass and heat between solid surfaces and free flowing air, cross and bulk flows are less than ideal for many of the applications which make it possible to manage internal climates in energy efficient ways.

Transient flows have very different characteristics in these scenarios. Turbulence eliminates the boundary conditions that limit surface-fluid exchanges, and because no constant pressure differentials are necessary to drive the flows, it is possible to create very local flows or mixing conditions. The hypothesis here also suggests that these flows can be driven through the interaction of geometry and low energy oscillation inputs in specific spatial localities, and that the flows are able to efficiently penetrate high surface area structures, enabling efficient use of solid storage of heat and water.

These transient mechanisms may therefore allow for precise control of convection flows which can vary over time and space, without requiring separate and continuous channels or mechanically actuated valves. This would create opportunities to integrate a range of functionalities in single, non-discrete building components which can add new performance, or replace a fraction of the large diameter tubing installations which take up significant space in contemporary architecture.

1.3 The structure and contribution of this thesis

This thesis is structured into nine chapters. The first three form the background; after the introduction follows a chapter on industrial relevance, then the literature review. After this follow four chapters documenting the experiments conducted, of which the last is a chapter discussing potential building implementations of the explored mechanisms. The final two chapters present a wider discussion and the final conclusions.

1.3.1 The building industry: digital processes and complexity of form

Following the introduction, chapter two, *The building industry: digital processes and complexity of form*, addresses the background and motivation of this thesis. The contemporary demands on the built environment are pushing the industry towards increasing performance on the one hand, and a reduced ecological footprint on the other. Such demands are evident in the western world through client expectations and stringent building regulations, but equally important in the increasingly affluent and rapidly growing populations of the developing world where client needs can be widely different from western standards, and where infrastructure and context are placing a great emphasis on innovation and new solutions which rely less on centralised, externalised resources such as electricity.

Many actors in the construction industry are currently moving towards an increasing digitalisation of the design and fabrication process. The most striking example of this is the development of construction scale additive manufacturing, a technology which is actively explored by Laing O'Rourke, the industry sponsor of this thesis. One of the expected advantages of such a fabrication process is the ability to produce building components with highly complex internal and external geometries. In conventional fabrication, complexity of form carries a high economic penalty, but in additive fabrication this no longer the case, making unique customisation and elaborate detailing feasible.

The processes described in this thesis are capable of using this complexity of shape in ways which deliver increased functionality within a building, potentially creating new economic value which justify the large scale implementation of such digital technologies in the construction industry.

1.3.2 Literature review

The internal climate is carefully regulated in today's construction, with extensive regulation determining minimum air change rates as well as standards for retaining heat, which is often in contradiction with ventilation which carries a heat loss penalty. Typically, the critical components of indoor climate are heat, pollution, and humidity levels, which together have significant effects on the well-being of both occupants and the building itself. Contemporary techniques for controlling these factors mostly rely on external energy input, mainly through the use of fans, heaters, and refrigeration devices. This chapter reviews a number of techniques from literature which have the potential to carry out such work with less energy expenditure, or by exploiting ambient energy sources. These include natural (wind driven) ventilation, thermal buffering, moisture buffering, evaporative cooling. These mechanisms all manage flows of different kinds: flows of air, heat, water, or in some cases phase transition, which allows advantageous trade-off's to be made: heat can be vented out in the cold hours of the night and morning, excessive water can be buffered in solid materials until the external conditions are more favourable, or polluted air can be vented through heat recovery devices. While contemporary research has made big strides in maximising the storage potential of such masses, for example via phase change materials, a recurring limitation is the ability to move heat and mass (mostly moisture) into and out of such solid mass at sufficiently high rates.

Flows of heat and water tends to be facilitated by airflows though convection. While turbulence arises in almost all systems, the main drivers of these techniques are steady (at least ideally) flows of air. Transience is rarely considered, even though it is a major contributor to most mass transfer systems, particularly at smaller scales and at interfaces.

Biological organisms tend to exploit these transient mechanisms as efficient ways of controlling flows in their direct and internal environment. One example, on which the research in this thesis is founded, is the termite mounds found in sub-Saharan Africa. These are biological structures that are created by and house termite colonies and symbiotic fungi. The nests are subterranean and sit below the mound, which mediates their exchange and connection to the surrounding environment. The colony has a significant metabolic activity and must get rid of large volumes of carbon dioxide and other by-products, and constantly replenish the supply of oxygen, while maintaining an internal homoeostatic environment. Previous research theories have understood these exchange mechanisms as continuous flow models, driven by stack effects or steady winds, not dissimilar to conventional building ventilation. However, recent research has demonstrated that these steady-state systems do not exist in at least some species of termite colonies, and instead proposed a transient model where the mound geometry interacts with turbulent and transient wind.

The understanding of these mechanisms is tentative, but a number of clues suggest that the termites modify the geometry of the mound – a complex reticulated network with considerable spatial variation – in ways which exploit the transient energy of ambient winds to move water vapour and respiratory gasses in a highly controlled manner.

1.3.3 Transient mass transfer mechanisms in termite egress complex

In this chapter is established, through a series of tracer gas experiments, that a 0-net, oscillating airflow of low amplitude (about an order of magnitude lower than the thickness of the panel, or a few millimetres) passing over a geometry of reticulated tunnels causes a significant increase of mass transfer rates across said geometry. As no net bulk flow occurs and the velocities involved correspond to laminar flow Reynolds numbers (White and Corfield 2006), there are no known mechanisms that would lead to a net mass transfer at the scales involved. However, the results presented here show that this does occur, and that this is true for the mound sample taken from the egress complex (EC) of the termite mound as well as a number of other geometries modelled on the EC.

The topology and geometry of the tunnel network is shown to influence the rate of mass transfer achieved, with an increasing reticulation leading to greater mass transfer rates relative to geometries with less reticulation. These reticulated geometries also exhibited greater tortuousity and larger surface areas, which contributed to a greater flow resistance to static flow. Thus the reticulation which contributes to increased transient flow rates, inhibits flow rates in static flow.

The rates are also found to be heavily influenced by the amplitude of oscillations, with increased mass transfer rates following on greater amplitudes, and are frequency dependent with a range of approximately 10-100 Hz oscillations, and the greatest effect is found around 30 Hz. The effects are shown to be material independent.

The oscillations, when passing across the tunnel network, give rise to large scale convection, which causes significant mixing of the air on the two sides of the panel. This flow appears to be of turbulent nature, but the specifics of the flow were not possible to determine in the set-up used, particularly at the interior of the tunnel network due to the opaque and 3-dimensional panels, which led to the experiments in the next chapter.

1.3.4 2-dimensional measurements of transient flow

Experiments were here conducted in a 2-dimensional environment using a liquid medium (water) and fluorescein dye in order to create an opportunity for clearer visualisation of the flow within the tunnel network. Dynamic similarity was maintained between the experiments by reducing the oscillation frequency in order to maintain constant Reynolds and Womersley numbers in accordance with literature.

It was found that similar effects were seen in the liquid medium, and that a greatly enhanced rate of mass transfer was observed with the application of oscillations of around 6 Hz. The oscillations led to strong turbulence within and in direct proximity to the tunnels, with an even distribution of dyes within the channel cross section indicating that the turbulent flow led to a very small or absent (laminar) boundary layer. This was contrasted to slow, steady flow where a considerable laminar boundary layer formed.

The mass transfer rates, and the emergence of turbulence within the network, were as before dependent on the reticulation of the node network, and the node-to-node distance (edge length) was determined to be significant. In the case where two geometries of the same overall width was compared, the one with more nodes and shorter edge length exhibited greater mass transfer rates, and the turbulence was more pronounced, particularly at lower amplitudes. The decrease in flow rate observed in the wider geometry was found to be much less than would be expected from *Frick's Law* which governs diffusion rates (and was expected to describe a mixing environment). This may be because of the increase of cross sectional area which increased the node count and compensated for the lower flow rates expected from the greater distance, or it may be because the flow rate was determined by bottleneck effects. Either way, it appears that the mechanisms are robust with regards to increases in overall geometry depth.

Finally, it was found that the turbulence formed at velocities which are significantly lower than what would be expected from Reynolds number analysis. There were thresholds both in frequency and amplitude, below which little or no turbulence emerged and the resulting mass transfer was near zero. These thresholds were influenced by the edge length, with a greater edge length requiring a greater amplitude in order to generate the turbulence.

1.3.5 Driving transient mass transfer through turbulent wind

The transient air flows investigated in the previous chapter are driven by a mechanical actuation resulting in a regular oscillation. Such mechanisms are not known to be present in the termite mounds from where the sample is taken, and if the same effects are assumed to take place in the egress complex in its natural condition, other sources of energy and transience must fill a similar role. A likely candidate is the winds found around the termite mounds which are known to be transient in nature. If the previously observed mass transfer effects can be generated from wind exposure alone, it would provide an advantageous method to exploit ambient energy and reduce reliance on electricity in architectural contexts.

It was found however, that while exposing the panels to external turbulence led to increased mass transfer (of a magnitude similar to the rates previously recorded), there was no difference between the different panels, i.e. reticulation did not appear to be a significant contributor. It was therefore concluded that the increased mass transfer was the result of the external turbulence penetrating the panels, rather than being generated internally. It should be noted however that the ventilated chamber was still a dead zone, so no cross flow occurred. In addition, the reticulated geometries did not exhibit lower mass transfer rates than the straight geometries, in spite of significantly higher resistance to steady flows, suggesting that there is an advantage to the reticulation ratio of transient to steady flow with respect to permeability. When comparing panels of different depth/thickness, it was found that the decrease in mass transfer rates in identical conditions were slightly less than what would be expected from a inversely proportional dependency, i.e. a doubling of the thickness resulted in less than a halving of the mass transfer rate.

This chapter also explores the thermal exchanges associated with the transient flow. It was found that, as would be expected, the heat loss through convection could be calculated from the thermal capacity of an equivalent continuous flow. The exchange between the panel and the flow across it was found to be large, with the incoming air equalising rapidly with the panel surface temperatures. The same observation held true for water vapour, and the relative humidity of the air surrounding the panels increased rapidly when the panels were saturated in water and the surfaces were wet. These results suggest that the the transient ventilation mechanisms can be advantageously employed for conditioning of incoming air, thermal buffering, or evaporative cooling.

1.3.6 Architectural application: structural integration of transient processes

This chapter explores how the structures and mechanisms documented and investigated in the two previous chapters may be implemented in architectural contexts. In the first section, it is proposed how a system for passive, distributed ventilation could be created by means of integrating a structured geometry in the building envelope based on the findings in chapter five, potentially assisted by induces oscillations. The benefits of such a system are argued: it is less dependent on electrical energy or mechanical moving parts; it does not lead to an elevation of indoor air velocities; the incoming air can be easily conditioned through heating, cooling or humidification/dehumidification; and it is free from fan noise and has other potential acoustic advantages. The drawbacks of such a system are discussed, primarily the potentially significant heat loss and the inability to use central heat recovery systems. Because of these issues it is suggested that the most appropriate implementation of such a system would be in climates which experience significant diurnal temperature variation, where the systems inherent ability to buffer heat can be taken advantage of. It is shown that by means of either a thin, external layer of insulation or an increased thermal heat capacity of the wall (achievable through he use of phase change materials (PCMs) or simply by increasing the wall thickness), the transient ventilation system can achieve an almost complete thermal buffering over diurnal cycles. If water is readily available, further reduction of temperatures can be achieved through the use of evaporative cooling as part of the system, either direct or indirect.

The findings in chapter three can be used in order to create *activated flux structures*, where the flow of energy (e.g. heat) or matter (e.g. water) between solid mass and adjacent volumes of air can be selectively enhanced using a low-energy, mechanically activated oscillation. This enables solid structural elements of a building to act as reserves of warmth, coolth[4], or water. The primary emphasis is heat management, as this is the largest factor in terms of building energy footprint as well as comfort, but humidity management is also explored as a potential. Existing literature suggest that current solutions of humidity management through buffering materials are limited by the absorption/desorption rates, and unable to respond quickly enough to dampen daily variations, and/or dependent on fan driven solutions.

The ability to control the level of exchange between the solid and air enables the use of highly effective asymmetric buffering solutions, one example of which is night time ventilation where the building core can be cooled during a short period of the diurnal cycle, allowing it to absorb a large amount of heat from the building during the day, causing the internal temperatures to be significantly lower than the average of the outside temperature without the use of air conditioning. It is discussed how such structures should be designed in order to achieve the highest effect, and a design strategy based on the egress complex is outlined.

1.3.7 Discussion

In this chapter is discussed the limitations of the research proposed, how it may fit into a greater context of engineering based on biological principles, and the directions this area of research may take in the future.

The research question of this thesis is one which touches on a number of fields that are not typically addressed in engineering and architecture, sitting at the intersection of biology and physics. In addition, the phenomena of transient turbulence are not well established or understood in any field. Because of this and the limits of my own experience and knowledge, the experiments have been undertaken in a relatively inductive way, and the results presented here are the outcome of a trial and error process. The value in the results lies therefore not primarily in establishing a mathematical theory which can explain why the turbulence arises, but rather in demonstrating that it happens and how it happens. I hope that these findings may inspire a more rigorous investigation of the involved phenomena by specialists in the relevant fields. Similarly, the findings have established with a reasonable certainty how these mechanisms can be controlled and utilised, but the emphasis and contribution is on the principles of such an implementation, rather than a fully developed and quantitatively tested product.

The following section discusses how the proposed systems may fit into current building practice. For the proposed transient ventilation systems, the primary concern is the industry trend towards increased building airtightness and heat conservation, particularly with regards to ventilation which is increasingly fitted with centralised heat recovery. Distributed transient ventilation obviously presents challenges for such building systems, and may not be suitable for colder climates because of this. But rather than rejecting such systems outright in cold climates, it is argued that transient ventilation can help create intermediate zones between inside and outside, whose use can change over seasons, time and the activity of users. This falls in line with the stated ambition to create a more diverse indoor climate, where a more dynamic and gradual interface between inside and outside can give a more effective use of space and energy. Furthermore, because the system

[4] i.e. a future potential for absorbing heat

proposed involves methods for controlling undesirable flows which arise due to spatial pressure differences between the different parts of the building, distinguishing it from a ’leaky’ envelope.

Here is also addressed the requirements for building the proposed structures in relation to what techniques and technologies are available today, and may be expected in the near future. It is concluded that the reticulated geometries could be fabricated using current technologies such as casting or CNC milling, but that this would require a trade off between function and cost, and this trade-off is expected to rapidly decrease in significance as construction scale additive manufacturing becomes available. This would open up numerous possibilities for functional integration, increasing the potential value added, which leads to the future implications of the work presented, particularly when regarded as a component of a functionally integrated, emergent building approach[5].

The nature of biological organisms is inherently non-linear, and observing a component of a physiological system, such as the egress complex of the studied termite mounds, means that the potential effects and benefits of the emergent whole can be lost. This is evident in this research as the mechanisms in the mound which translates the transient energy in the wind, via oscillations, to turbulent mixing (if such mechanisms exist) are not known. Further investigations into the mound physiology may open up new avenues which enables more flexibility and functionality at lesser energy cost. This interdependency and integration is further illustrated by the example of a different termite species, *Odontotermes obesus*. While closely related, these termites have radically different mounds, which utilise flows of air in other ways than the *M. michaelseni* mounds, and where the flows of air appear to be involved in maintaining the structural integrity of the mounds as well as regulating the respiratory gasses.

To gain the full value of the research outcomes documented in this thesis, it is likely that they need to be considered as a part of a larger change of building logic and approach. This is not least because of the high initial costs associated with additive manufacturing or other complex fabrication strategies, and the potential for synergy effects is likely needed to create viable business opportunities, at least for high volume markets where the impact can be the greatest.

1.3.8 Conclusion

The work in this thesis investigates the interaction of certain geometries with transient air flows. It demonstrates a mechanism through which the egress complex of the termite mound, as well as other similar geometries, acts as a catalyst for converting small scale oscillations to turbulent flows which lead to significant levels of mass transfer across the geometry. The turbulence occurred at low Reynolds numbers where turbulence would normally not be expected, and with a 0-net bulk flow, thus leaving no established models to explain the phenomenon. These results confirm hypotheses previously suggested in literature about mechanisms of transient mass transfer which could be present in termite mounds, and show how a dead space can be ventilated without cross-flow.

The phenomenon was shown to be dependent on certain geometric properties of the tunnel network, with the most significant being the reticulation and edge lengths. A more reticulated system exhibited greater mass transfer rates than the one with less reticulation, and fewer nodes/longer edges correlated to a decrease in mass transfer at a given amplitude and frequency.

The mass transfer thus induced by oscillations was shown to be highly controllable: the difference of mass transfer rates between the unperturbed system and the one activated through

[5]As opposed to the reductionist view which dominates contemporary design and engineering.

oscillations was up to at least two orders of magnitude. The mass transfer rate was strongly influenced by the oscillation amplitude, with results suggesting that the rate scales to the square of the amplitude, and by the frequency of the oscillations. It was also shown that certain geometric arrangements are tuned to particular input flow characteristics, e.g. node-to-node length and oscillation amplitude, and that the responses scale non-linearly, which provides a mechanism for discriminatory flows within the mound.

The increase of mass transfer rates was shown to be caused by the emergence of large scale, turbulent convection within and adjacent to the tunnel network. A consequence of this flow pattern is that no laminar boundary layer forms, and that the exchange of heat and matter between the air flow and the surfaces of the tunnel network is therefore significant, a finding which was confirmed both experimentally and theoretically.

The architectural usefulness of the mechanism is based primarily on the air flows acting as carriers of heat or moisture, though in some cases the air flow itself can be useful, i.e. for ventilation. These flows can be used to selectively capture ambient energy when external conditions are favourable, and transfer these to the building interior via a buffering/storage system.

Its effectiveness derives from the controllability of the flows and the strong interaction/exchange between the mass and the air. The former provides an alternative to systems of pumps or fans acting together with valves to control flows in a selective manner. This function is a result of the possibility to create a spatially diversified network of channels where the local network properties allows for turbulence, and resulting mixing/mass transfer, to be selectively turned on or off by the application of variable oscillation frequencies. This is particularly useful when integrating such functionalities in non-discrete building components, and allows for a single network to be used to accomplish multiple functions in contrast to a pipe which is limited to a single flow path. The latter, the exchange of heat or moisture between the tunnel walls and the air flowing in them, can maximise the effectiveness of thermal or moisture storage devices, and is particularly useful in combination with high-performance materials where heat exchange is often an application bottleneck. The high rate of thermal and moisture exchange depends on two factors: the turbulent boundary layer, which promotes near-wall mixing relative to steady, laminar flows; and the ability of the mass transfer to effectively penetrate into high surface area geometries, where steady cross flows would either be limited by flow resistance or would be unable to penetrate due to dead zone conditions.

Other than the building and the functional system itself, the potential of this strategy for climate regulation is determined by the availability of ambient resources. For this purpose, the more variable the climate, e.g. large diurnal temperature variations, and the more direct sunlight or wind, the better the system can perform. In addition, if the average ambient temperature is close to the ideal indoor temperature, fluctuations are easier to compensate. Such conditions are found in many parts of the developing world, which is experiencing rapid economic growth and where demands for indoor comfort are increasing. If passive or semi-passive solutions based in part on the transient mechanisms described here can upgrade the current building standard, it would provide an opportunity to create desirable living conditions without the negative ecological impact that regrettably has been the consequence of the high comfort and living standard in the developed world.

1.4 Industrial and academic context

This thesis has been written at the UCL Centre in Virtual Environments, Interaction and Visualisation (VEIV), a doctoral training centre at University College London. The VEIV centre specialises in the intersection of architecture and computer science, and a diverse group of researchers explore issues pertaining to both virtual and physical environments by developing computational tools for analysis and generative purposes. As an Engineering Doctorate, this research was undertaken in collaboration with and through support by an industrial sponsor, Laing O'Rourke.

Laing O'Rourke are a multinational construction company which, though their internal consultancy and research group Engineering Excellence Group, are pursuing large scale innovation in the construction industry. The topic of his research project is central to Laing O'Rourke's interest in the development of digital fabrication techniques as it explores the potential added value that can be derived from the capabilities of such techniques and processes, and furthers the understanding of the generation and function of the potentially resulting complex geometries.

Chapter 2

The Building Industry: Digital Processes and Complexity of Form

Architecture is in the process of revolutionary transformation.

– Rivka and Robert Oxman[1]

2.1 Perfomative architecture

The context of this thesis is a world where the digitalisation of design and fabrication has become increasingly prevalent. New technologies emerge with an increasing pace, and innovative practitioners are slowly reshaping the processes that generate the built environment. As the new practices mature and seep from the realms of avant-garde and academia to the everyday and the vernacular, the impact can hardly be overstated. In *The Materialisation of the Digital World*, Malé-Alemany (2012) writes:

> The materialisation of the digital world made possible by new fabrication tools will have a significant number of economic and sociocultural effects: we are all of us potential fabricators, we can fabricate anywhere – meaning the production is completely de-localized – and carry out our own customized fabrication. Which practically means that we are able to reinvent the world: invent it for ourselves and build it together.

[1](Oxman and Oxman 2010, p.15)

> How is the creative process affected by the possibility of giving physical form to ideas and mental structures whose natural environment is digital? Are we really going to be able to build anything our imagination throws up? What new forms await us? What kind of barriers will crop up on the creative horizon as a result of the shift of the digital realm into the physical world? These are exciting questions, the answers of which are necessarily speculative.

Malé-Alemany speaks about the emerging technologies of additive fabrication, which have gone from obscure specialist technology to mainstream applications in the very last few years. Such technologies are typically associated with high value, low weight applications where slow fabrication times and high volume costs are traded for high resolution, which is the opposite of where construction fabrication is typically found. However, as will be shown below, additive technologies are currently being developed for the construction scale which are more suited for the demands of architectural application (Soar and Andreen 2012).

These efforts are not only pursued academically, but have garnered the interest and effort of large scale construction and development companies: Skanska has recently stepped in as the main sponsor of the large scale additive fabrication development at Loughborough University, and Laing O'Rourke are developing an in-house technology ("FreeFab") aimed at using additive technologies for complex panel fabrication. From a business perspective this can be justified either from cost savings or by the ability to create new product value which is not possible to achieve using conventional construction processes. The former, while potentially feasible in the long run, appears to be far out of reach considering the high cost of additive manufacturing relative to the typical costs in today's building materials and processes. In terms of added value, the potential is significant but relatively unexplored.

Additive fabrication stands out from most other fabrication processes through the capacity to generate highly complex and custom geometries. This is true from a absolute perspective – certain geometries are essentially impossible to fabricate suing subtractive or formative technologies but can be 'printed' – as well as a relative perspective, where the critical issue is marginal cost. Theoretically, in an additive process the cost of printing is only influenced by the amount of material used (though this is only partly true in most real processes). This is in contrast to subtractive or formative processes where the biggest influence on cost is often shape and where cost tends to increase rapidly with increased complexity. Thus the marginal cost of custom geometries and geometric complexity is often exponential in formative or subtractive processes, but linear (or flat/negative) in additive fabrication (within the boundaries of the process).

The potential of construction scale additive manufacturing (AM_C) as a business case can therefore be seen from the perspective of marginal cost versus marginal value: if increasing complexity and customisation can generate significant added value at at small or negligible cost, the high initial cost of AM_C can be justified. This added value can potentially be found in representational or cultural preferences and in external cost reduction, but in order to gain a significant advantage over conventional processes it can be argued that the key is *integrated functionality* and *local adaptability*. The integrated nature of functionality is important, because it implies a departure from construction conventions where functions are separated into discrete components, instead replacing this approach with a continuity of locally differentiated form. In the article *Manufacturing Performance*, Menges (2008) discusses the work at Freeform Construction / Loughborough University which

> ...contributes to establishing an alternative approach for designing performative architecture where form, material, structure and performance are understood as inherently related and integral aspects of the manufacturing and construction process. [...] Sooner than most of us may anticipate, the synthesis of novel design approaches based on emergent systems and physiological processes in sync with emerging manufacturing capabilities will enable architects to embed and integrate manifold performance capacities in the fabric of our habitats.

The work presented in this thesis demonstrates one such way of utilising geometric shape to add functionality in the built structure. The ability to control flows of heat, water and air within a building are critical for the demands which are increasingly placed upon human habitats: reducing energy consumption, reducing exotic material use, improving comfort. As sustainability issues continue to draw the public's attention, and as new markets open up due to increasing prosperity and expanding populations, the market value of building performance which reduces energy footprint and simultaneously increases comfort will be significant.

2.2 Digital manufacturing

In the construction industry, automation and computer control is less widely implemented than in many other areas, perhaps mostly due to the prototypical nature of the industry and the scale and cost of individual project which cause legal risks and limits the ability to spread investments across large production runs (Crowley 1998). But whatever the reason for the relatively slow implementation, the digital is today reshaping construction processes at an increasing pace. Initially limited to mass produced component fabrication, digital construction is starting to evolve into mass customisation (Da Silveira, Borenstein and Fogliatto 2001; Tseng and Jiao 2001), involving processes which manage a rapidly increasing geometric complexity and uniqueness. Digital fabrication technologies can roughly be classified in three categories: formative, subtractive and additive[2]. The former two are the ones which have been most widely implemented as of today, but inroads into additive fabrication have been made and the technology is potentially highly disruptive.

2.2.1 Additive manufacturing

Additive technologies span from conventional or even vernacular architectural fabrication techniques such as brick laying and timber constructions, to highly technical layer-by-layer fabrication techniques utilised in 3D-printers. They have in common the method of building up the whole from a large amount of small components or units. The global form comes from the arrangement of the sub-units rather than the shape of them (which distinguishes these techniques from assemblies made from components made using subtractive or formative processes).

Additive manufacturing in the form of 3D-printing is typically categorised based on the starting material and solidification process used. An incomplete list includes extrusion techniques or fused deposition modelling (FDM); techniques based on a powder material which can either be sintered

[2]The latter of these, additive, is particular in the context of construction as (contrary to what is the case in other fabrication industries) there is a strong precedent for additive processes in traditional architecture. "Additive manufacturing" is typically used to describe 3D-printing techniques, which is the definition used in this thesis. Other digital techniques also fall under the additive umbrella, such as the work by Gramazio and Kohler (2008), are referred to simply as digital additive techniques (or technologies.)

(selective laser sintering, or SLS) or fused chemically using a liquid[3]; and polymerisation of a liquid photopolymer, typically using a laser, of which the most common method is stereolithography (SLA). Typically, these processes are slow and costly, but can achieve very high resolution and geometric freedom. The process is such that every fabricated part is unique, and there are no cost or time penalties involved in mass customisation relative to repetitive series.

There is a current trend towards greater diversity of fabrication materials and towards processes which are more flexible in terms of cost and speed. These advantages come at a cost of accuracy and resolution, but in construction scales these are typically not critical. Such developments involve opens source printers such as RepRap (Jones et al. 2011) and its multitude of derivatives. Often these derivatives are based on FDM techniques, as they are suitable for inexpensive builds and rapid deposition of larger volumes. In some cases they also involve typical construction materials such as clay or other mineral based compounds.

2.2.2 Additive manufacturing at architectural scales

Additive manufacturing has at the the present time found a significant place in the production industries, particularly through its competitiveness in short-run, high-value products, and is increasingly used for end-use products and not just for prototyping and mould-making. Typically, these are scenarios which are quite different from typical architectural fabrication – particularly because of the cost per volume/weight (Soar and Andreen 2012). However, the custom nature of architectural production makes the prospect of such implementations appealing, and several research and commercialisation efforts are currently taking place in order to bring additive fabrication to the construction industry in a viable form.

The beginning of construction scale additive manufacturing (AM_C) can be traced back to Pegna (1997), who experimented with and showed the feasibility of selective curing and consolidation of cement powder and sand through controlled application of steam.

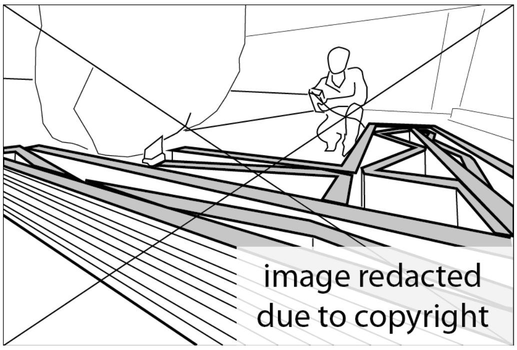
Pegna was followed by the *Contour Crafting* technology developed by Khoshnevis, Bukkapatnam et al. (2001) and Khoshnevis (2004) which used a trowel and nozzle design combined with backfilling or internal lattices in order to build an automated construction system intended primarily for large volume and fast pace construction. Khoshnevis has later proposed the employment of Contour Crafting technology for Moon-based construction, using Lunar regolith as a material (Khoshnevis and Bodiford 2005). The concrete printing development has been carried forward by Loughborough University which are developing a large scale concrete printer which uses FDM extrusion (Buswell et al. 2007; Lim et al. 2012). The Loughborough lab has been successful in printing objects of the scale of about one meter cubed, notably double curvature building panels and furniture, and are integrating functional voids and reinforcement. A third process currently being developed is D-Shape, which is the creatinon of Enrico Dini and which was patented in 2004 (Soar and Andreen 2012). The process uses a non-organic binder which transforms the sand-like material into a solid mineral with micro-crystalline characteristics (Dini 2014).

In addition to academic research and small scale boutique solutions, there is also a growing interest from large construction firms to embrace the AM_C technologies. This is seen in the recent announcement that Skanska has launched a venture together with Loughborough University and a number of collaborators including Foster + Partners, robotics firm ABB and aggregates suppliers

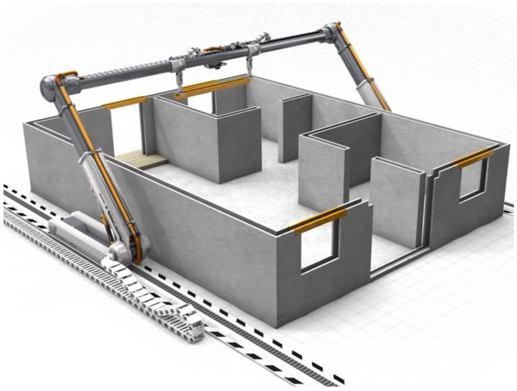
[3]These techniques are technically what is referred to as *3D printing*, however this word has come to be used as an umbrella term for all additive manufacturing techniques.

(a) Concrete Printing | Loughborough University. Photographer: Agnese Sanvito

(b) D-Shape | Enrico Dini



(c) Concrete 3D print process | WinSun



(d) Contour Crafting | Behrok Khoshnevis. Artwork: Sebastian Bertram

Figure 2.1: Construction scale additive manufacturing.

Buchan Concrete and Lafarge Tarmac. The agreement includes licensing for the concrete printing techniques developed at Loughborough, and Skanska hopes to build an AM_C supply chain (Withers 2014).

The same year, construction firm Laing O'Rourke has announced the internally developed FreeFab system (Gardiner and Janssen 2014). FreeFab is based on the recognition that functional AM_C is still some way off, and is instead intended to leverage the advantages of the technique by printing large scale wax moulds for complex pre-cast concrete panels without the cost and waste associated with conventional techniques. The technique is intended to casts large components, up to 6x4 m, and therefore prioritizes speed over resolution, relying on a milling spindle to achieve higher surface finish as needed, an approach similar to what has previously been proposed by Freeform Construction Ltd (Soar and Andreen 2012).

2.2.3 Function of shape

Additive manufacturing is particular relative to other fabrication and manufacturing technologies primarily because of two significant differences. The unit cost is independent of how many units are produced, which eliminates the need for standardisation as we are habituated to expect. Further, the cost is independent of the complexity of the form produced[4]; this is analogous to biological organisms where shape and complexity does not cost resources, only the total use of material does.

[4]At least in theory: in practice complex shapes still have, in most cases, a significant penalty in the form of longer tool-paths, need for scaffolding material, and processing times. It is not unreasonable to assume that this penalty will diminish with the development of new technologies (Campbell, Bourell and Gibson 2012).

Such characteristics, while most pronounced in the case of AM, are found in many emerging digital technologies: architecture is today being produced with levels of complexity and customisation which has previously been impossible in all but the most time-consuming manual labour scenarios (Scheurer 2010).

Nature provides an almost endless example of functional form: the physiology of biological organisms are structured, at scales ranging from molecular to the size of a body (and in some cases even larger), in ways which enable the form to sustain the organism. This is not without importance of material, but in the biological organism the distinction of shape and material is fluid and interlinked, the two being so closely interrelated as to make them impossible to separate.

Functional shape in nature is linked to interfaces, areas where flows and transfer take place, e.g. through the absorption of oxygen by a cell. As the size of organisms increase, basic tasks such as the aforementioned absorption of oxygen from its environment becomes complicated; this stems from the simple scalar relationships between volume and surface: as volume increases so does surface, but at a much slower rate. The solution is to fold the emerging shapes: the single cell grows not to a sphere, but develops into a sheet or long string, first forming a ring, then folding over itself in a creased pattern in order to maximise the interface with the environment. As the organisms develops into larger and larger entities, this folded relationship is maintained, creating an increasingly complex assembly, constantly tailored to maintain the critical interfaces. The outcome as the folding is repeated at increasing scales is a structure which is fractal[5], and rather than smooth and continuous it is discontinuous, heterogeneous, and irregular (Deering and West 1992).

Such structures are able to exploit or create gradient in the local environment, controlling the flow of matter and energy through the use of membranes or local environmental conditions. By building up potentials (steep gradients), work can be generated and desirable outcomes encouraged. The amount of work that can be performed is minuscule, but the large interfaces of the folded structures allow the effect to be multiplied. This flow of matter and energy across organisms is the essence of the biological processes, and has to be carefully balanced with the structural integrity of the organism, coping with pressures from the built up gradients or at larger scales from gravity and locomotion. While specialist structures exist in our bodies, which are particularly tailored to manage stress from gravity or locomotion, such as the bones of mammals and other animals, this is not a functional separation. Every organ and cell has a structural component, and likewise do bones not only cater to structural loads. The bone is an organ which, just like any other, caters to a multitude of flows, processes and gradients, and is continually negotiating these to best accommodate its needs and minimise expenditures.

Material, scale, and form

In architecture and construction, practitioners tend to think of material and form as discrete entities, where *form* is limited to scales over a centimetre or so[6] , and any smaller formal attributes are considered *material.* However, this distinction ignores the fact that what is carelessly described as material is relative, and is in reality created by an interaction of the elements and the shapes those are arranged in. This is true at the molecular levels, where atoms bond together in crystal

[5]The fractal geometry of nature was of course fist investigated by Benoit Mandelbrot (1983) in the book with the same name.

[6]This distinction is to a degree arbitrary, and what is considered material effect varies from case to case and between professions.

or amorphous patterns and where the arrangements of atoms correlate to the properties of macro-structure, but it is equally true at larger scales: insulators are not typically resistant to heat flow because of their own molecular properties, but because of how they are arranged in space, trapping air and limiting its motion.

Such arrangements are commonly found in biological structures: two prominent examples are trabecular bone structures or the arrangement of wood fibres (figure 2.2). Both of these structures gain extensive strength from the arrangement of fibres, and the relationship of the growth patterns of wood grain and its ability to manage load and stress has been extensively studied by for example Mattheck (1998). In addition, living structures such as these are capable of a vast variety of functionality particularly in terms of flows, in these cases the relatively straightforward flow of water and nutrients through the wood fibres (xylem and pholem) and in the case of bone tissue an even greater diversity of functionality.

(a) Trabecular structure of femur bone.

(b) Wood grain

Figure 2.2: Functional arrangement of material

Additive manufacturing technologies are commonly thought to create homogeneous masses of solid material. This is however a limited view of the capabilities of such a system, as is being investigated in a large range of research. In mechanical engineering, the term *functionally graded materials* have come to denote “materials that comprise a spatial gradation in structure and/or composition, tailored for a specific performance or function” (Reimanis 2004). Examples include variable density printing, variations of properties such as the force constant of a spring achieved by altering the material thickness, or the ability to create an almost textile fluidity of normally solid materials through the integration of hinges or interlocking mechanisms in manners similar to chain mail armour of the past. Hanna (2007) demonstrates how both topology and local density/thickness can be used to optimise the performance of a structural lattice, in ways reminiscent of the structuring of bone or wood grain shown in figure 2.2.

The chair *Beast* by Neri Oxman (2010) exemplifies another approach which incorporates multi-material printing, adapting the properties of a chair to the human body which will inhabit it though the local choice of material as well as shape in the form of thickness, pattern density and curvature. The properties of material and form interact, reinforce or compensate each others’ behaviour and characteristics. Such an approach challenges the conventional assumptions of linear material behaviour, as the relative position of each subjectively defined unit of material effects its properties. This enhances the potentials of the design, but expands the design complexity by orders of magnitude, forcing a redefinition of design as well as fabrication strategies.

With the emergence of additive fabrication is coming a new fluidity across scales. Conventional thinking and methods limit the internal structure of components to a relatively homogeneous range of scales. Going beyond this range requires the assembly of hierarchies and arrays of discrete components. With additive technologies it is possible to design structures where the resolution approaches the micron, allowing a hierarchical treatment of scale within the same element. The work done by Beckett and Babu (2014) at the Digital Manufacturing Centre in London (figure 2.3) demonstrates the potential of such approaches using selective laser sintering to create architectural objects which border on the surreal, incorporating textural, sensual and structural functionalities in a seamless whole.

While additive fabrication at the scale of micron is not likely to be prominently featured in AM_C scales in the near future, the expanded range of scalar hierarchies applies nevertheless but with a range from the millimetre to several metres, and it is fully feasible to incorporate elements of conventional AM into a larger digitally fabricated complex, through AM_C or other techniques. This will open up new avenues for higher-level functional integration (Menges 2008; Pasquire, Soar and Gibb 2006), and how this can be best exploited is a research area full of unexplored potential.

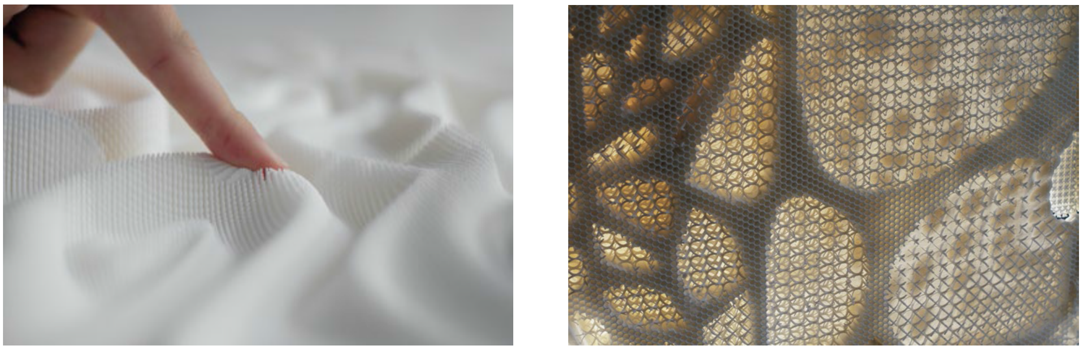


Figure 2.3: Multi-scalar, high resolution additve manufacturing. From (Beckett and Babu 2014).

2.2.4 Generative design Strategies for integrated function

The changes in architectural fabrication outlined above are creating a host of challenges for design; these challenges come from the increasing complexity of form, but of even greater importance is the fact that a non-linear relationship is introduced between and within elements, where the behaviour of each local instance of material is influenced by its immediate neighbourhood. Such challenges need to be addressed through bottom-up design strategies, which are capable of dealing with the inherent non-linearity and extensive research is currently being carried out in such areas by a wide range of researchers such as Hensel, Menges and Weinstock (2006), Hanna (2007), Terzidis (2008) and Andrasek and Andreen (2015), among many others.

This is not to imply that a unified, self-organizing algorithm which is capable of describing a full building is necessary to deploy the strategies suggested here, many may even be fully applicable within a conventional building paradigm at little loss of function. But algorithmic means of describing integrated design processes, whether limited or fully inclusive can fundamentally extend our ability to employ and control the benefits and function of integrated shape and material treatment of the complexity which is made possible by contemporary digital fabrication technologies.

2.3 Contemporary challenges in building design

In parallel to the technological developments which are having a profound effect on the making of architectural space, new demands are emerging on the function and perception of architecture. These relate on the one hand to the increasing awareness of the impact the built environment has on the ecological system which it inhabits, and on the other to humanitarian, societal and economical challenges, some of which have been with us since the beginning of civilisation and some of which are connected to recent developments in human society.

These challenges are roughly separated into those which deal with the demand for resources and the ecological impact (issues of ecological sustainability), and those which deal new and old functional demands of buildings (issues of societal sustainability and individual needs and desires). In much of today's technology the means we have of fulfilling one has a detrimental effect on the other; reducing carbon emissions imply decreasing thermal conditioning of indoor air, building new houses with greater comfort imply increased use of resources and a greater ecological impact.

As the traditional methods of achieving this greater performance (increased functionality) are returning less and less, both because of technological constraints (see Bentley (2007) on *the complexity ceiling*) and because of pressures to reduce energy and resource consumed, architects and designers are forced to move into new strategies.

2.3.1 Sustainability

The built environment has a substantial effect on the ecosystems surrounding it on all scales – from the global to the local. Detrimental effects arise from the use of resources (material and energy) used to create the building and the ongoing operational demands. The most significant environmental challenge is that of greenhouse gasses and their effect on global climate. IPCC (2014) estimates that we already see widespread effects on physical, biological and human/managed systems from anthropogenic global warming, and that these will become much more severe in the future. In order to achieve a peak temperature increase below 2°C – which is considered an optimistic though not optimal scenario that has been agreed upon by governments globally (International Energy Agency 2013a) – a significant decrease of carbon emissions is required on short notice, and overall energy consumption must be limited as well as increasing the share of non-carbon energy sources.

Buildings account for about a third of the global greenhouse gas (GHG) emissions, and the main source is energy consumption. 85-95% of a building GHG emissions is estimated to be generated during the occupation phase (Thormark 2006). In order to reduce these detrimental effects architecture should be designed and built in manners which reduce both the impact from construction and from the occupational phase, though the emphasis is on the latter. The current trend, in spite of significant achievements in green building practice, is that building energy consumption is up: European figures average at 1.5% annual increase, with a faster rate of increase in more southern countries, where the absolute figures are lower. HVAC systems account for a large part of building energy consumption, approximately 50% in the US (Pérez-Lombard, Ortiz and Pout 2008), and addressing this requires efforts that go beyond conventional thinking.

Looking beyond the problems of global GHG emissions, buildings are a significant source of pollution, particularly in construction phase. Their erection often leads to destruction of ecological habitat, which is further exacerbated by the hostility of the built environment to diverse ecosystems. A challenge for the industry when dealing with GHG emissions is to address these issues without causing additional strain on the local ecosystem, either through pollution associated by the extraction and processing of building material, or through effect of the buildings themselves. The increased reliance on exotic materials and highly sealed and insulated buildings/environments which tend to follow energy reduction risks placing additional loads on the environment.

2.3.2 Emerging markets and developing economies

As has been alluded to above, buildings in northern, industrialised countries have a larger carbon footprint than those in more southerly countries. This is due partly to greater heating requirements, but it is also a matter of relative wealth and technological level. This feeds into a trend of increasing energy consumption in the building sector, the Energy Information Administration (EIA) forecasts that energy use in the built environment will grow 34% over the coming 20 years. Growth is expected to continue in developed countries, particularly due to installation of new appliances, but the greatest increase will be found in developing countries. It is estimated that that the developed world will experience a doubling in the energy consumption in the service sector in the next 35 years (Pérez-Lombard, Ortiz and Pout 2008).

International Energy Agency (2013b) predicts that the energy demand of South East Asia will increase 80% in 20 years, which correlates to a 200% increase in the size of the economy and a 25% population increase. Similarly, Sub-Saharan Africa, which today accounts for only a very small part of CO_2 emissions is set to grow rapidly in terms of both economy and population. This region is resource rich, but currently less than a third of the population has access to electricity and the costs are among the highest in the world. The region contains 13% of the worlds population, but only 4% of its energy demand (International Energy Agency 2014).

With increasing prosperity and population, we expect the demands on architecture, in terms of function, size and comfort, to increase significantly over the coming decades. Climates in these regions are typically warmer than what is common in the developed countries, and most building currently rely on passive internal climate regulation, if they have any at all. Should the development here follow the example set by hot, arid developed countries such as the South-Western US, an enormous increase in the use of HVAC can be expected which may not be possible to accommodate within the bounds of the goals which have been set relating to energy consumption and GHG emissions. However, such regions are also full of potentials for developing new best practice: The lack of existing building stock and infrastructure in combination with the abundant renewable resources means the costs for new practices are less than they would be in already developed countries. In addition, the climates of such regions are more suited to alternative approaches for climate control due to the lack of extreme cold, and there is a strong vernacular and historic precedent of building solutions which are passive and naturally ventilated.

Overall this forms a picture of a significant part of the world which has previously seen little of modern construction and resource consumption, but which is rapidly developing and are acquiring both the means and the desire to live in indoor environments which deliver higher comfort standards. The challenge for the construction industry is to create a new built environment which is not modelled on the precedent of the developed world, but one which uses the abundant local resources and unique climates and traditions in order to deliver high comfort without reliance on vast amounts of externally supplied electricity.

2.3.3 Increased expectations of performance

While there is significant pressure for energy consumption in building use and construction to go down, consumers are constantly seeking increased performance. Such performance takes many forms, and in architecture is is often difficult to measure as it is not limited to quantitative functions such as air quality and temperature but includes subjective and qualitative characteristics. In the past (and present, to a great extent) such performance has been achieved by relatively linear increases of the quantitative aspects of construction: increasing capacity of HVAC, increasing building area, increasing wall thickness. However, in a context of diminishing resources such approaches are difficult if not impossible as they rely on increased resource consumption (though the opposite relationship exists as well, e.g. by increasing insulation the initial resource demand goes up, but over time it decreases.)

In addition, performance increases of much technology is achieved through miniaturisation which is particularly evident in electronics; such miniaturisation allows greater functionality at a lower resource and energy cost[7]. But as the construction industry deals with quantities which are not possible to shrink in this way – flows of air, water, heat or structural forces – miniaturisation cannot solve the fundamental compromise between functionality and resource consumption. As demands on performance increase, the “space between the spaces”, the walls, slabs and service ducts, become increasingly valuable. The problem is that these spaces cannot be indefinitely expanded as the cost increases not only in resources but in loss of effective building area, a problem which is exacerbated in tall or large buildings with extensive service needs.

To resolve this conundrum, architecture is then reliant on other strategies than miniaturisation. One such strategy is to combine functionality and achieve many objectives through a single structure. Such *deep integration* structures are commonly found in biological organisms – one organ rarely performs a single duty but is designed to achieve many objectives. A typical example is the bone found in our own bodies. As a superficially simple structure, bones perform an array of functions in our bodies: they provide support and protection, enable movement of the body, function as storage for minerals and energy, and within them the production of blood cells take place. In addition, the bones allow for the internal and external flows of cells and other matter which keep them alive and continually changing. Such integration is achieved greatly through the manipulation of the specific geometries, as can be seen in figure 2.2, and the distribution of material is a negotiated process, incorporating many objectives until the structure is elegantly matched to function (Turner 2012).

2.4 Conclusions

The trends of contemporary architecture described in this chapter outline a scenario where on the one hand the need for innovation and novel solutions is vast: it is imperative to reduce the resource demands of the built environment, while accommodating an constantly increasing desire for increased performance, and to build modern, comfortable buildings for a part of the world which has previously existed without modern technology and comfort. On the other hand the building

[7]See *Moore's Law* in Wikipedia: “*Moore's law* is the observation that, over the history of computing hardware, the number of transistors in a dense integrated circuit doubles approximately every two years. [...] This exponential improvement has dramatically enhanced the effect of digital electronics in nearly every segment of the world economy. Moore's law describes a driving force of technological and social change, productivity, and economic growth in the late twentieth and early twenty-first centuries.”

industry is experiencing rapid change, where fabrication and design processes are shifting towards digital practice, and where fundamentally new capabilities and approaches are being introduced.

Within this premise, I have argued, lies the possibility to use these emerging capabilities to devise architectural solutions which are capable of delivering more, at a lower cost. These architectural solutions all hinge on a capability to model, fabricate, predict and understand complexity. The development of such capabilities are clear for anyone who observes the industry, though they are still limited and often associated with high costs, but there is a lot of questioning as to how we can use it for increased benefit beyond trend, fashion and style.

This thesis seeks out to investigate and demonstrate how we can use such complexity (of form, in this case) in ways which are compatible with the current building practices, and which expands on the tools available to the designer in order to deliver functionality in architecture.

Chapter 3

Literature Review

The harmonious melding of structure and function – biological design – is a striking feature of complex living systems.

– J. Scott Turner[1]

3.1 Introduction

The problems addressed in this thesis revolve around the use and manipulation of transient flows of air in order to beneficially alter the internal climate of buildings, potentially reducing the use of external energy while improving human comfort and efficiency. This chapter will review the foundations for the hypothesis proposed in the introduction: that such flows can be altered through complex geometries integrated into the building envelope of other elements, and that they can be used to carry out work in the building environment.

The review is structured into three main sections: The first addresses the larger scale mechanisms involved in building climate regulation. This demonstrates how mass transfer can be applied for internal climate regulation, and in some cases provide a performance benchmark. Typically, the strategies described are reliant on static flows, and the transient flow mechanisms described later can potentially be used to improve these large scale regulation and ventilation strategies. This is particularly true for some vernacular, natural and passive strategies, which are typically very energy efficient but lack in controllability or efficiency. This lays the groundwork for later suggestions, outlined in chapter 7, on how these problems can be addressed through transient

[1] (Turner 2008, p.76)

mechanisms. This section also establishes the conventions and regulatory demands placed on indoor environments, particularly in Northern Europe, and the current methods used in achieving these demands.

After this follows a section which describes transient and non-laminar flows. This includes some of the basic properties of such flows and how they may be applied in the context of mass transfer, as a mean of extrapolating behaviour and function. This section relies on both engineering/physics literature and biological, particularly physiological, literature. In physiology, such flows have been carefully considered as they often play an important role in biology, whereas very few studies or exist within the engineering field, at least at the scales (centimetres to meters) which are the focus of these studies.

The final section is a study of the existing research and theories of gas transport in termite mounds, on which much of the research described in this thesis is founded. It is described how previous models assuming static flows (such as stack or thermosiphon effects) are insufficient to explain the circulation found in the mounds of the termite species *Macrotermes michelseni* found in the Namibian savannah. It is explained how current research suggests that a transient air flow model is more consistent with experimental results, and how such a model is proposed to function. This section also contains extensive information on the internal geometry and structure of the termite mounds in question. This thesis builds extensively on this physiological research and attempts to extend it in ways which enable the application of similar principles in architectural context, through the combination of the experimentally tested transient phenomena in combination with vernacular or contemporary climate regulation strategies shown in section 3.2.

3.2 Building ventilation and climate control

The managing of internal climates has a number of end goals, largely dealing with inhabitant health and comfort, and to a lesser extent building health and integrity. The most significant of these is to keep air fresh and avoid build-up of pollutants, water, odours and carbon dioxide. This is mostly accomplished by replacing internal air with fresh outdoor air. However, the other main goal is to maintain a temperature within the building which falls within the thermal comfort thresholds of the occupant, and as the internal temperatures often differ from the external temperatures, these aims are contradictory. The warmth (or coolth) lost to ventilation must be restored through other means which is often electric energy, contributing to the building's ecological footprint. In addition, thermal comfort can be affected by a number of other effects related to mass transfer, most significantly humidity levels and air velocity. These parameters are strongly influenced by a wide range of factors stretching from the external conditions, through personal preferences, to building construction and the specific mechanisms for mass transfer used, creating constrained and complex design space, where trade-offs in one area must be accepted to accomplish increased functionality elsewhere. It is therefore suggested in this thesis that the ability of the designer to create a well functioning and low energy building can be extended by increasing the range of mechanisms available for mass transfer, specifically by introducing transient and turbulent flows in a controllable manner.

Ventilation of indoor air is a significant design consideration for any modern building, and the demands for reliability and capacity increase as greater air tightness is achieved, e.g. in passivhaus standard buildings. The typical trend in the construction industry has been to move from passive, or natural, ventilation as is typically found in historic and vernacular architecture to highly engineered mechanical ventilation as the only way to achieve sufficient performance in comfort, reliability and ecological sustainability. This thesis investigates *active natural* ventilation alternatives largely modelled on physiological principles found in biological organisms as a high performance and ecologically sustainable alternative to mechanical climate control and ventilation.

3.2.1 Demands on building climate

Building ventilation serves a number of purposes. Primary among these is the removal of contaminants and by-products from indoor air, along with replacement of oxygen consumed within the building and in some cases the removal of excessive heat and humidity generated internally. Contaminants pose potential health hazards (Hollowell 2011; Hughes and O'Brien 1986; Seppänen and Fisk 2004; Sundell et al. 2011; Jones 1999) and can lead to discomfort and reduced occupant performance (Bakó-Biró et al. 2012; Dimitroulopoulou 2012). In addition to the demands from the building occupants, inadequate ventilation can be a danger to the building itself, causing moisture build up which lead to direct and indirect damages to building components (Klintberg, Johannesson and Björk 2008; Seppänen and Fisk 2004).

Health

Pollutants found in indoor air can be generated by the occupants and their activities or by the building or the environment itself. The former is a significant comfort issue, but activities such as cooking or smoking can generate dangerous contaminants and much office equipment cause significant levels of contaminants (Hughes and O'Brien 1986; Hollowell 2011). In addition, biological contaminants such as bacteria and viruses are released to the indoor environment and are detrimental to health (Jones 1999). Non-occupant sources include contaminants from building and furniture materials which can release chemicals such as volatile organic compounds (VOCs), radon or asbestos, the ground which in some cases can be a significant source of radon, or from the ventilation system itself which can be a source of biological contaminants such as fungi, bacteria and viruses (Jones 1999; Seppänen and Fisk 2004).

An adequate level of ventilation reduces the risk of these health hazards. Dilution of contaminants reduce the health risks associated with said contaminants, and in addition ventilation has a strong effect on humidity levels, which influence occupant health directly or indirectly, as it influences levels of dust-mites, which cause allergic symptoms, and micro-organism growth (Seppänen and Fisk 2004).

It has been shown that lower ventilation rates are associated with increased health risks, specifically ventilation rates above 25 l/s per person in office environments reduce the prevalence of sick building syndrome symptoms; inflammation, respiratory infections, asthma symptoms and short term sick leave increase with lower ventilation rates; and home ventilation rates above 0.5 air-changes per second have been associated with lower risk for allergic manifestations among children in Nordic countries (Sundell et al. 2011).

Some health related hazards may however increase with increased ventilation if the contaminants are present in outdoor air. This is particularly the case with allergy inducing pollen (Seppänen and Fisk 2004).

Other significant comfort factors include minimal noise (particularly from the ventilation system), reduction of draughts in cold climates, and the temperature of the fresh air, which should be as close to the ambient indoor temperature as possible (Cotterell and Dadeby 2012).

Comfort

The ventilation system used has a significant effect on the comfort of its occupants. Effective factors include thermal comfort, dryness or excessive humidity, pollutants and odours (Melikov and Kaczmarczyk 2012; Bakó-Biró et al. 2012; Seppänen and Fisk 2004).

Thermal comfort is affected by air velocity (which tends to increase with increased ventilation) as well as potential deviation from optimal temperatures which can only be avoided by heating or cooling the outdoor air at an energy cost. Increased air velocity is used in warm climates to increase the tolerance threshold for high temperatures. A study found that increased air velocity could compensate for a decrease in perceived air quality due to an elevated temperature from 20°C to 26°C (Melikov and Kaczmarczyk 2012). Conversely, exposure to draughts exacerbate the perceived discomfort from temperatures below optimal (Toftum and Nielsen 1996), particularly if the airflow is highly turbulent (Fanger et al. 1988).

The impact of insufficient ventilation has been investigated in schools where the pupils' performance (memory, concentration and attention) was negatively influenced by low ventilation rates (Bakó-Biró et al. 2012). In the course of the study the ventilation rates in the classrooms were increased from 1 l/s per person to 8 l/s per person. The classrooms had measured CO_2 concentrations as high as 5,000 ppm before the intervention. As a result of the changes, performance metrics went up between 2.2% and 15%. Similarly, Seppänen and Fisk (2004) cites several studies showing enhanced performance by office workers as ventilation rates increase.

Ventilation of building envelope

In addition to ventilation of indoor air, the building envelope itself is often susceptible to structural damage due to moisture build-up, and ensuring ventilation of envelope components is of great significance (De Freitas, Abrantes and Crausse 1996; Klintberg, Johannesson and Björk 2008). The damages may occur from microbial growth (for organic components), erosion, or because of loss of structural integrity as a direct consequence of increased water content (Lawrence et al. 2009; Sandin 1993).

In order to minimise the risk for excessive moisture build-up in the building envelope a number of strategies can be considered. First, the in-flow of water should be minimised. Sources of water are either external (e.g. rain, outdoor humidity) or internal. Internal moisture is mostly a problem in case of leaks or during winter, when a large temperature differential between indoor and outdoor air can cause condensation within the building envelope, called interstitial condensation (Sandin 1993; Cotterell and Dadeby 2012). Second, the outflow of water from the wall should be maximised. This can be either through ventilation (Klintberg, Johannesson and Björk 2008) or capillary migration to the outside of the walls (De Freitas, Abrantes and Crausse 1996). In addition the risks can be decreased is the envelope components have a buffering capacity which dampen spatial or temporal extremes (Hens 2012).

Statutory requirements

Building regulations across Europe vary, but generally tend to cluster around 0.5 air-changes per hour (Dimitroulopoulou 2012).

In Sweden, Swedish Building Regulations BBR 2012 stipulate a minimum continuous flow of 0.35 l/s per m^2 floor area, equivalent of 0.5 air-changes per hour for a ceiling height of 2.5 m, which may be lower (0.1 l/s) in unoccupied rooms. In addition, outdoor air should mainly enter the buildings in rooms intended for social interaction and rest, and air should be removed from the building in rooms with lower demands for air quality, such as bathrooms. Air flows should be limited to 0.15 m/s in occupied rooms in order to minimise discomfort from draughts (*Regelsamling för byggande, BBR2012* 2011). For office environments, guidelines prescribe an additional airflow of 7 l/s per person on top of 0.35 l/s per m^2 floor area.

3.2.2 Natural ventilation systems

Natural ventilation is defined as ventilation which is driven by naturally occurring differences in air pressures, cased most often by wind or stack effects (through solar gain) (Khan, Su and Riffat 2008). While it is the norm in historic and vernacular architecture, it is often not considered in contemporary buildings due to the difficulty of predicting and maintaining a steady performance (Schulze and Eicker 2013), including a significant lack of regulations and guidelines as well as know-how and simulation tools. Further limitations of natural ventilation include energy efficiency in cold climates when the intake air has to be heated, achieving high ventilation rates for high occupancy buildings and ventilating deep floor plan buildings. In some scenarios natural ventilation is avoided because of the complexity it introduces, for example in high rise buildings where significant differences in wind behaviour and pressure exist between different floors (Omer 2008).

In spite of these difficulties, natural ventilation has significant advantages over mechanical ventilation particularly in light of the need to reduce external energy footprint (Schulze and Eicker 2013; Lomas and Ji 2009; Lomas 2007). Energy savings typically derive from reduced or eliminated energy consumption of electric fans, and reduced air-conditioning needs (Schulze and Eicker 2013).

Khan, Su and Riffat (2008) categorises natural ventilation into *passive* and *active*, with a subcategory of *directed passive* ventilation. The distinction in these categories is made by the the presence or absence of moving parts, which makes the system active (the exception being directed passive which moves with the wind but in a much simpler manner than the active systems).

Passive wind driven ventilation

Window openings (or similar openings) are the most common passive ventilation systems, and are usually considered in either single sided ventilation (Warren and Parkins 1985) or cross ventilation scenarios (Mochida et al. 2005). Cross ventilation is relatively well understood, and there are methods outlined for controlling directions and volume of flow outlined in literature, by adjusting the placement of windows, building components and features (primarily vegetation) outside of the building (Mochida et al. 2005). Single sided ventilation which does not rely in cross flows is more complex, and both stack effects (due to temperature variations across the building envelope) and the turbulent components of wind play a significant role in addition to steady pressure differentials, which can affect ventilation flow either through aerodynamic interaction with the window opening or mean pressure differences in the cases where there are more than one window opening (Warren and Parkins 1985). Window openings on their own are generally only acceptable as ventilation systems in dwellings, where manual operability and the low-tech approach are significant benefits. In more complex buildings they are too limiting, primarily due to the significant variation and unpredictability in the driving wind forces (Khan, Su and Riffat 2008).

Wing walls can be used to enhance single sided ventilation from windward facing windows. A wing wall is placed perpendicular to the wall between two window openings, and induces positive and negative pressures by the two openings, driving a flow between them. The ventilation gain can be significant, causing a 150% increase in average velocity in the room (Khan, Su and Riffat 2008) , but the architectural drawbacks are often prohibitive, e.g. blocking out light.

Courtyards and atria are common ventilation techniques which have been used historically particularly in the Middle East and Mediterranean region to achieve summer cooling. These generally work by creating an upwards flow of air from the courtyard or atrium, and pulling air from inside the house. The upwards flow can be driven by convection due to heating of the courtyard air, or by wind forces. In certain scenarios courtyards and atria can also funnel air into the building, however this had been determined less effective from a cooling perspective (Khan, Su and Riffat 2008). If two court yards are connected to a building whereas one is shaded and the other sunny, air flow from the cooler one to the hotter will form, creating an agreeable climate in the intermediate spaces (Coch 1998).

Chimney/exhaust cowls are designed to dissipate exhaust air to the atmosphere through internally generated heat convection, stack effect or wind induced suction. Their performance are dependent on the wind conditions, and when immobile they are not able to operate at full efficiency at all times. This is addressed partly by movable chimney cowls, covered later.

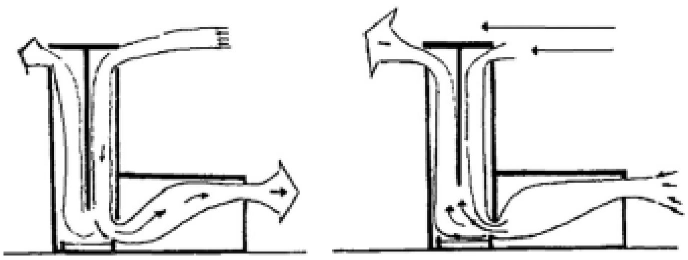


Figure 3.1: Operating principle of a wind tower. Adapted from (Khan, Su and Riffat 2008).

Wind towers and wind catchers are similar to chimney cowls, and are typically found in Middle Eastern architecture. They are structures built up to a higher elevation than the building specifically to capture the higher wind velocities found at higher elevations, though they may also utilise stack effects (figure 3.1). The tower or structure can have one or several openings that can act as an inlet or outlet for wind flows (Khan, Su and Riffat 2008). In Middle-Eastern wind towers, called *malqaf*, the tower opening typically faces the prevailing wind, with outlets provided at ground level. The size of the opening is affected by the outside air temperature - higher temperatures mean smaller openings which allows a greater contact area with the construction material which can cool the inlet air during the hottest periods of the day due to buffering effects. To enhance this, the wind tower is often placed on the northern, shaded side of the building (Fathy 1986).

Contemporary *double skin façades* often operate with similar principles to wind towers.

Directed passive wind driven ventilation

A *Wind cowl/scoop* is a structure similar to a chimney cowl, but which is designed to either face the wind (in which case it acts as a flow intake) or face away from the wind (in which case it acts as a flow outlet though suction), and which can rotate around an axis in order to always face the same direction relative to the wind. They are often used in conjunction with wind towers. Studies have found that cowls used to create a positive pressure (generate an inward flow) are significantly more effective than cowls designed to create suction (Khan, Su and Riffat 2008).

An innovative variation of the wind cowl is a *wing jetter system*, which is designed like an aerofoil placed over the exhaust opening. Much like a upside down air plane wing, this aerofoil creates a negative pressure at the exhaust opening pulling air out of the building. A large rudder ensures that the wing jetter always faces the wind. The wing jetter has been shown to work well in a wide range of wind speeds, but the flow generated is significantly smaller than an equivalent turbine ventilator. The flow of a 1.5 by 1.5 meter wing catcher was measured to 110 l/s at a wind speed of 6 m/s (Khan, Su and Riffat 2008).

Active wind driven ventilation

Turbine ventilators are wind-driven air extractors. They are constructed from a number of vertical airfoils placed in a circular array which generate positive and negative pressures when wind blows across the turbine, creating rotary movement. In some versions this rotation is connected to a fan at the inside of the duct, which serves to create a negative pressure and extract air from the building, whereas more simple versions the turbine itself creates negative pressure when set to rotate. In the absence of wind, the turbine ventilator can facilitate ventilation through stack effect. There exists various versions of the turbine generators, which utilize various mechanisms for assisting or improving the effect. These include solar assisted fans which increase the outflow, and vertical axis wind extractors especially designed to operate at maximum efficiency in urban, turbulent conditions (Khan, Su and Riffat 2008).

3.2.3 Mechanical ventilation systems

With the increased building airtightness and ventilation that followed on the energy crisis of the 1970's, followed a number of problems for buildings and occupants due to inadequate ventilation. This let to an increased adoption of mechanical ventilations systems. In middle-western Europe these are most commonly simple mechanical exhaust systems, whereas in northern Europe it is more common with heat recovery ventilation. In southern Europe natural ventilation still dominates due to the lesser prevalence of high insulation and airtightness (Laverge, Pattyn and Janssens 2013). Heat recovery ventilation exists in a number of variants, and is part of a larger category of mechanical exhaust and inlet systems.

Mechanical exhaust ventilation

Mechanical exhaust systems are relatively simple, being constructed from a number of independent exhaust fans typically placed in wet areas such as bathrooms and kitchens. These exhausts create a negative pressure in the building, which pulls outside air into the building either through existing leaky parts of the building envelope of through dedicated vents, placed for example by windows. This ensures a flow within the building that prevents odours to infiltrate areas for rest and social interaction (Laverge, Pattyn and Janssens 2013). Current UK best practice guidance requires an energy consumption in fans of <0.6 W/l/s(Energy Saving Trust 2006).

Mechanical exhaust and inlet

This type of 'whole house' ventilation uses mechanical control of both inlet and outlet air. Compared to a simple mechanical exhaust system it tends to be more complex, typically with a centralised air distribution system which requires space-taking ducts and more noise. However, it allows for the use of heat recovery mechanisms and integrated air conditioning systems. In residential buildings even a fully mechanical system is typically coupled with operable windows to complement the mechanical system for peak loads (Cotterell and Dadeby 2012). Current UK best practice guidance requires an energy consumption in fans of <1W/l/s, in combination with heat recovery (see below)(Energy Saving Trust 2006).

Heat recovery ventilation

Mechanical Ventilation with Heat recovery (MVHR) is part of Passivhaus standards, and utilise a counter-flow heat exchange chamber to warm the incoming air from the exhaust air. In a heat exchanger the two air flows do not mix, but the heat is allowed to pass from one to the other (figure 3.2. The use of a counterflow mechanism allows a very high efficiency which means most heat energy can be recovered. However, for these systems to be effective, a very low air leakage through the building envelope is required. Beside preventing the loss of energy that normally follows any ventilation, the heat recovery allows the incoming air to be conditioned to approximately ambient indoor temperature, thereby eliminating or reducing could draughts. In Passivhaus standard the system is dimensioned to deliver air at minimum 16.5°C when the outside air temperature is -10°C (Cotterell and Dadeby 2012).

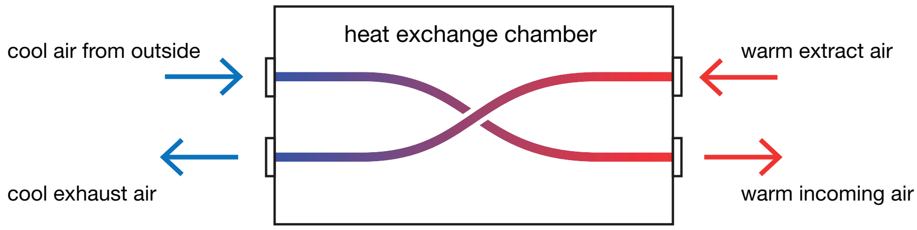


Figure 3.2: Counter flow heat exchanger. Adapted from (Cotterell and Dadeby 2012).

Exhaust air heat pump systems

Exhaust Air Heat Pumps (EAHP) have been common in Sweden since the 1980's, and share with MVHR systems that they recover part of the energy present in the exhaust air, but the do not utilise a heat exchanger. Rather, the building's primary heating comes from a heat pump which utilises the exhaust. Compared to conventional air-to-air heat pumps which extract heat from outdoor air these systems can significantly reduce the electric input needed for operating the heat pump (Fehrm, Reiners and Ungemach 2002). Geros et al. (2005) studied the influence on the surrounding built fabric, specifically night ventilation from spaces in urban canyons, and found that that this influences the efficiency of the ventilation significantly,

3.2.4 Dynamic insulation

Dynamic Insulation is a concept which integrates a distributed ventilation flow in the buildings envelope in a distributed mode, drawing air through the insulation and thereby recuperating heat which would otherwise been lost to the outside (Taylor and Imbabi 1998). The system is effectively a distributed counterflow heat exchanger. Because of the large envelope area over which the air is drawn, the air velocity can be considerably lower than in conventional ventilation, and as the air is drawn through the porous insulation material this acts as an effective filtration unit, removing pollutants from the fresh air (Imbabi 2006). In an experimental test case, the system is shown to lower a wall construction's dynamic U-value to 0.1 W/m^{2}K relative to 0.26 W/m^{2}K for the static case (Baker 2003).

For the system to be effective, it is necessary to maintain a constant negative pressure internally, and that the rest of the building is air tight. This is achieved by a centralised mechanical exhaust ventilation, and it is worth noting that this need to be coupled with a heat recovery system in order to be competitive with the energy efficiency of current MVHR or EAHP systems.

The potential drawbacks of dynamic insulation is the dependence on a constant pressure differential between the inside and outside. While the internal pressure is relatively easy to maintain, external pressures vary significantly both spatially and temporally as has been detailed above. This means that different walls of the building may experience significant differences in relative pressure difference over the dynamic insulation, and this may change rapidly with winds and turbulence. If the flow rate deviates too much from the ideal, the system loses efficiency, and if the flow is reversed the energy gains are reversed to significant energy losses. If a location is positioned so that it is constantly experiencing a reversed pressure differential, this can lead to significant condensation as the warm indoor air flows out into the wall and is cooled off. Other potential problems include the risk of volatile compounds in the construction materials, such as VOC's, mould (though mould growth may be inhibited by the abundant ventilation) or flame retardants, which can flow with the air into the building interior.

3.2.5 Night cooling ventilation

Indoor climate is not only related to air quality and ventilation, but also the management of temperature, moisture levels and a number of other factors. Night Cooling Ventilation (NCV) is a method for managing building heat rather than air supply, and relies on the cooler night time temperatures to lower the average indoor temperature by increasing the ventilation rates at night. Data indicates that night cooling ventilation typically decreases the peak day temperature with 3°C, which is significant for increasing comfort, or in the case of air conditioned buildings decreasing energy usage (Santamouris, Sfakianaki and Pavlou 2010; Givoni 1992). The efficiency of NCV is dependent on the temperature difference between night time ambient air and indoor temperatures, the flow of ambient air, and the thermal capacity of the storage medium as well as the heat flux between indoor air (or potentially ambient air if this is in direct contact with the storage medium) and the storage medium. Geros et al. (2005) investigated the effects of the built fabric around the ventilated building, specifically ventilating from urban canyons, and found a significant decrease of the efficiency of the technique in these conditions caused mainly by higher temperatures and lower winds speeds. this indicates that such techniques need to be addressed in the context of the greater design decisions, and should not be considered in isolation.

3.2.6 Building airtightness

During the last decades, building airtightness in Europe has steadily increased (Sherman and Chan 2006). The change is particularly prominent in Northern Europe because the need to reduce the building's heat loss and associated energy footprint. In a naturally ventilated building, and for many types of mechanical ventilation, airtightness is directly linked to ventilation rate, with an associated trade-off between ventilation and energy loss due to temperature differences between inside and outside. In the most simple ventilation systems no distinction is made between air leakage and ventilation. Because of this, many European buildings are today insufficiently ventilated with significant problems in both inhabitant and building health (Dimitroulopoulou 2012).

However, in mechanical ventilation systems with heat recovery such as MVHR or EAHP, this relationship can be decoupled as the air exchange taking place through ventilation is significantly reduced. The implementation of such systems coupled with very airtight buildings is being driven forward by the increasing adoption of Passivhaus standards.[2] Passivhaus standards stipulate

[2] A *passivhaus* is a dwelling which maintains internal comfort temperature without the addition of external energy beyond what is generated from building occupants and household machinery. A number of strategies are defined in the standard in order to achieve this: avoiding air leakage, avoiding thermal bridges, moisture management,

an airtightness measured at a differential pressure of ±50 Pa (not to be confused with building ventilation rates measured without an artificial pressure differential) of 0.6 airchanges per hour. This can be compared to equivalent national statutory standards shown in table 3.1.

	Statutory/ volontary	Standard	Equivalent air changes per hour for average-sized house
France	statutory	0.8-2.5 $m^3/hr/m^2$ @ 4Pa	11
UK Building Regulations 2010 (England and Wales)	statutory	Max $10m^3/hr/m^2$ @ 50Pa	10
USA	statutory	Max $1.6m^3/hr/m^2$ @ 4Pa	8.5
Switzerland	statutory	Max $0.75m^3/hr/m^2$ @ 4Pa	3.3
UK zero carbon	statutory from 2016	Max $3m^3/hr/m^2$ @ 50Pa	3
Sweden	statutory	Max $0.8l/s/m^2$ @ 50Pa	2.88
Canada Super-E	voluntary	Max 1.5ach @ 50Pa	1.5
Passivhaus	voluntary	Max 0.6ach @ 50Pa	0.6

Table 3.1: International airtightness standards. (Adapted from (Cotterell and Dadeby 2012)

Very low air leakage has a number of benefits, primary of which is the reduced loss of heat energy. This loss occurs through the temperature difference between the escaping indoor air and the outdoor air which replaces is, and also because of decreased performance of the building insulation as air leaks into the insulation material. In addition to these direct energy savings, low air leakage creates a more comfortable indoor climate due to reduced indoor air velocity. It is argued that an air velocity ≤0.1 m/s, which is ensured by the passivhaus standard) results in occupants setting the thermostat as much as 2°C lower (Cotterell and Dadeby 2012).

As the airtightness of the building envelope increases, particularly at the boundary between the envelope and the environment, the ventilation of the envelope itself goes down which can potentially lead to humidity problems as water gets trapped within the structure. The source of the water can be environmental (e.g. rain and humidity), come from water leaks, or because of interstitial condensation, which occurs when war indoor air moves into the cooler envelope where the lower temperature reduces the vapour carrying capacity of the air and condensation occurs. In order to prevent these problems, two strategies are used. The first is to ensure adequate 'escape paths' for any trapped water, often though air gaps in the structure (Klintberg, Johannesson and Björk 2008). The second is to minimise permeability between the indoor air and the envelope. Specifically, the vapour permeability of the internal barrier of the envelope should be significantly more airtight than the external barrier (Cotterell and Dadeby 2012; Hens 2012).

3.2.7 Thermal mass and inertia

A building's thermal comfort can be greatly influenced by the thermal mass of the building elements. The primary mechanism is the thermal inertia of such a mass, which will tend to even out extremes in the building temperature, and in warm climates it may be particularly effective when combined with increased night ventilation. Architectures which utilize thermal inertia are commonly found in vernacular traditions, particularly in cold and temperate climates and in hot, arid climates (Zhai and Previtali 2010).

ventilation, and insulation (Cotterell and Dadeby 2012).

Thermal mass in vernacular architecture

In colder climates, the thermal mass is often a secondary characteristic of the massive materials which are used because of their thermal insulation properties and reduced infiltration which help to retain heat generated by internal sources. In contrast, buildings found in hotter climates with large diurnal temperature variations are constructed to exploit the thermal inertia of the massive construction materials which absorb heat during the day, reducing the indoor temperatures, and release heat during the cold nights (Zhai and Previtali 2010). This effect is enhanced by night-time cooling caused by radiative heat exchange with the clear skies, which allows the outside faces of the walls to cool below ambient temperatures. (Al-Hinai, Batty and Probert 1993). Buildings found here are also typically arranged in a tight arrangement which minimises the solar irradiation and thus the effective heat gain during the day. In addition, constructions in these climates are often more or less porous with greater infiltration rates which takes advantage of dry winds, sometimes through the use of elaborate constructions such as wind towers (Coch 1998).

In hot, humid climates, the temperature tends to remain high even during night, and thermal inertia carries less benefits. In these climates buildings tend to be constructed from light weight materials, and rely on solar shading and sir movement to maintain thermal comfort. These structures are often carefully tailored to local micro-climate variations and prevailing winds (Zhai and Previtali 2010; Al-Hinai, Batty and Probert 1993).

Contemporary use and parameters of thermal inertia

In a contemporary building design, heat storage can serve a number of functions, catagorized by Zhang et al. (2007) as:

> (1) the ability to narrow the gap between the peak and off-peak loads of electricity demand; (2) the ability to save operative fees by shifting the electrical consumption from peak periods to off-peak periods since the cost of electricity at night is 1/3 to 1/5 of that during the day; (3) the ability to utilize solar energy continuously, storing solar energy during the day, and releasing it at night, particularly for space heating in winter by reducing diurnal temperature fluctuation thus improving the degree of thermal comfort; (4) the ability to store the natural cooling by ventilation at night in summer and to release it to decrease the room temperature during the day, thus reducing the cooling load of air conditioning.

These benefits differ from the vernacular uses mainly in the way that thermal inertia can be used in conjunction with space heating and cooling in order to optimise use of external energy, which can carry a significant time dependent variability in cost and availability.

The ability of a material to convey thermal inertia to a building depends on two factors, the capacity for heat storage and the ability of that heat to transfer between the mass and the indoor air and environment. The former is determined by the density of the material and the specific heat capacity (for sensible heat) or specific latent heat of fusion or vaporization (for phase change). The latter, heat flux in and out of the mass, is affected by material properties (conductivity), geometry of the material (surface area, thickness), and the flow velocity of the surrounding air (or alternative liquids or gasses) (Lamberg and Sirén 2003).

In order to get the maximim benefit out of the thermal mass, a number of technologies have been investigated which are designed to enhance these characteristics.

Phase change materials

Phase Change Materials (PCM) are designed to utilise latent heat rather than sensible heat, i.e. the heat storage potential when a material changes phase. PCMs can provide high thermal energy storage density over a narrow temperature range which makes them well suited for contemporary buildings which typically exhibit small temperature variations (Zhang et al. 2007; Lamberg and Sirén 2003). The materials used typically have a melting point between 18°C and 28°C, and come in organic or inorganic form. Inorganic PCMs are typically hydrated salts and have multiple benefits including high energy density, relatively high thermal conductivity, non-flammable, and a low price. However, they also have severe drawbacks, including being highly corrosive and prone to phase separation. Organic PCMs on the other hand are more compatible with building materials, but are flammable, have a low heat conductivity and a variable volume (Zhang et al. 2007).

The PCMs are incorporated into the building structure though a number of methods which according to Zhang et al. (2007) include: *Direct Incorporation* where liquid or powdered PCM is mixed with conventional building materials such as concrete or gypsum; *immersion*, where porous building materials are immersed in melted PCM which is absorbed into the material pores; *encapsulation*, where PCMs are encapsulated in pods, sheets, rods etc., which protects the building material from adverse effects; and *laminated PCM boards* incorporating PCMs as a continuous sheet board in the building envelope.

A common problem with PCMs is the typical low heat conductivity. A number of techniques exist for mitigating this problem, including active methods such as agitators and stirrers, addition of dispersed high conductivity particles or composite materials, or various forms of geometric manipulations (Lamberg and Sirén 2003). Geometric manipulations affect heat transfer by minimising the internal distance within the PCM which minimises the negative consequences of the low conductivity, and by maximising the surface area which is the interface with surrounding media, thereby creating steeper gradients and faster heat flux. The most common way of doing this is by micro-encapsulation or by incorporating fins into the PCM material (Lamberg and Sirén 2003).

A particularly interesting application for PCMs is in combination with night cooling ventilations systems. In these cases cool night time air is led into a PCM energy store causing the solidification of the PCM, which are then allowed to melt and thus absorb heat during the day. The advantage over solid materials is primarily the narrow temperature range over which the heat uptake and release takes place, allowing a narrow range of day time and night time indoor temperature, and the high energy density per mass (Zalba et al. 2004).

Zhang et al. (2007) identifies three areas where PCM research and development needs further investigation and which are highly relevant for the mechanisms discussed in this thesis: 1. Integration method of PCMs in the building envelope. Currently the trade off between economics and efficiency of solutions is problematic. 2. Heat transfer enhancement. Current solutions lack the transfer rates required to obtain a designed thermal output. 3. Combination of PCMs with natural resources and active systems. Natural resources that could be combined with PCM energy storage include solar energy, night sky radiation, cooling ventilation. Similarly active systems such as heat pumps or solar collectors could be integrated in a PCM system.

Thermally activated building systems

Thermally Activated Building Systems (TABS) are systems which use the building structure, usually concrete slabs, to deliver cooling or heating to a building. This allows for the incorporation of the building's thermal mass into the HVAC system, which carries the benefit of reducing peak energy usage. In addition, the large surface area available means the systems can achieve significant heat flux between space and structure even for relatively low temperature differences, which in turn allows for the use of low energy heating or cooling sources - such as most natural sources. TABS use pipes to carry water for heating or cooling into the slabs (or other structural element) (Rijksen, Wisse and Schijndel 2010; Lehmann, Dorer and Koschenz 2007).

A consequence of TABS systems is that the structure of the building needs to be thermally exposed, thick and thermally insulating surface finishes can severely impede the system's effectiveness.

3.2.8 Humidity buffering

An area which has received increased research attention in later years is indoor humidity rates and building material moisture buffering capacity. The relative humidity level in indoor air impacts the health of the occupants, the health of the building, and the perceived indoor air quality. In addition, buildings with special purposes such as museums require a very tight control of moisture in order to protects objects housed within the building.

Elevated levels of humidity are directly and indirectly detrimental to human health because it may increase the proliferation of dust mites, which are known to cause allergic complications, promote micro-organism growth in both bacteria and fungi as well as infection rates, increase respiratory problems such as asthma, and increase the reactivity of irritant air pollutants (Wolkoff and Kjaergaard 2007; Arundel et al. 1986; Woloszyn et al. 2009). Further, interstitial condensation and fungus growth can be detrimental to building structures (Osanyintola and Simonson 2006; Padfield 1998). Similarly, low levels of humidity is associated with improved conditions for bacteria and viruses, increased risk for respiratory infections and asthma, and leads to higher levels of ozone in the indoor environment (Arundel et al. 1986). Overall, a relative humidity level of 40-60% is found to minimize adverse health effects (figure 3.3) and building condition.

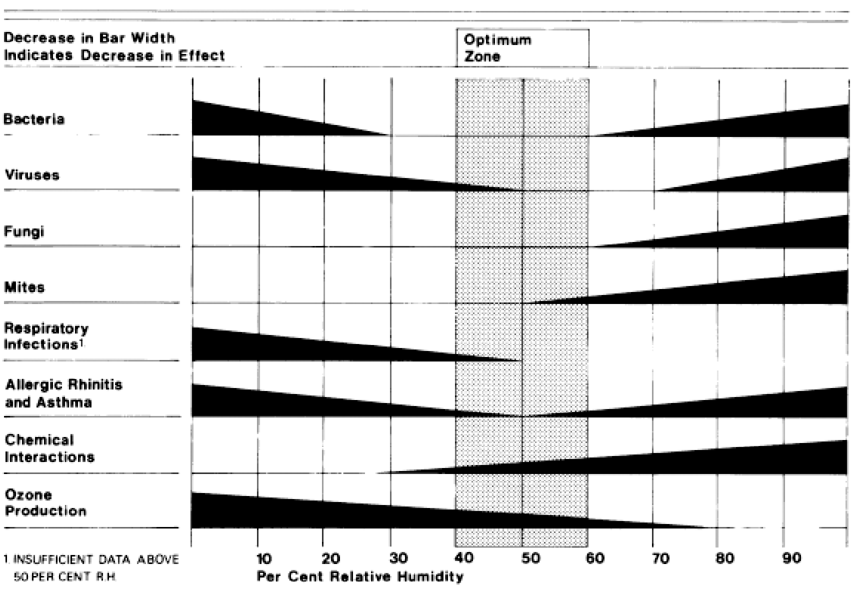


Figure 3.3: Optimum relative humidity range for minimizing adverse health effects. From (Arundel et al. 1986)

Moisture levels of indoor air tends to vary with the ambient conditions, but can be heavily influenced by building activity. This includes direct effects such as cooking, showering, etc., which cause a local spike in relative humidity where the activity takes place as well as increasing the average indoor humidity levels, and indirect effects mainly due to the temperature difference between indoor and outdoor air. As outdoor air is brought in to the building and is heated the relative humidity level decreases because of the increased capacity of hotter air to hold water vapour (Hens 2012).

The indoor humidity rate is also affected by the interaction between air-born moisture and hygroscopic building materials. The effect of these interactions is to moderate the relative humidity in the indoor air and reduce extreme humidity values towards the average (Rode et al. 2005). The materials which have the optimum characteristics for acting as moisture buffers have a large ability for water storage, and take up vapour near the 60% RH upper limit, and release it at 40% RH. An example of the beneficial effects of significant moisture buffering is the Suffolk Record Office in Ipswich UK, which is filled with paper records that have a significant humidity buffering capacity. The building is unventilated and only heated in winter. RH was tracked for a yearly cycle by Padfield and Jensen (2011), and was found to vary between 52% and 58% in a gentle annual cycle. Osanyintola and Simonson (2006) has investigated the potential energy savings from hygroscopic materials as moisture buffers, and concluded that a significant potential for energy savings of 7-8% in heated buildings, and up to 10-50% in buildings with air conditioning situated in hot, humid climates.

While many traditional building materials have exhibited significant moisture buffering ability, contemporary construction systems and materials are limited, often by design, in this ability. This is partly due to desired longevity and stain resistance (see modern paints, varnishes, sealants), and partly to prevent interstitial condensation caused by warm indoor air coming into contact with cold surfaces in the building envelope.

Building materials which exhibit good moisture buffering potential include wood (particularly with exposed end grain which has a strong effect on penetration depth and sorption rates), unfired clay bricks, cellular concrete. Surface treatments such as paint have a significant negative impact on the buffering capacity of the materials, and even thin and permeable surface treatments reduce the effect (Rode et al. 2005). Padfield and Jensen (2011) compares the buffering capacity of a number of materials while also including ambient flow conditions and geometric variations. The results are shown in table 3.2.

Leaving aside material differences, a number of observations are significant in these findings. Increased surface area has a strong effect on the buffering capacity, particularly over shorter cycles (up to 96 hours), which indicates that the water transfer within the material is a limiting factor. In addition, air movement is critical for utilising the maximum potential of the material, with the best effects found when a fan was actively pushing air through the perforations in the bricks. Covering the bricks with a thin layer of No. 1 filter paper restricted the airflow into the perforations, and therefore cut the buffering capacity to 25%.

In a postscript to (Padfield and Jensen 2011), Padfield, Jensen and Ryhl-Svendsen (2012) outlines a full scale experiment testing the humidity buffering of unfired clay bricks in a building interior. The test room was 26 m^3 and a total wall area of 56 m^2, which was painted concrete, and two of the walls were outer. The measured air change rate was 0.125 ACH. On the internal corner of the wall was fitted 7.5 m^2 of 110 mm thick unfired brick, 2.5 m^2 of which were perforated. The main purpose of the experiment was to verify simulation data, but the results gave good indications

Material	mm	B24	B-96	B-long	B-static
Unfired massive brick	53	10	21	-	165
Unfired perforated brick	53	27	58	108	136
Unfired perforated brick, double	106	39	95	196	272
Unfired perforated brick, double, low airflow	106	10	21	-	272
Unfired perforated brick, double, paper cover	106	10	26	98	272
Unfired perforated brick, double, fan ventilated	110	61	108	243	271
End grain wood	40	15	34	-	122
Cellular concrete	50	7	9	-	17
Fired perforated brick	52	-	-	3	12

Table 3.2: Buffer values (volume of air which can be buffered from a given area of construction material) for a number of test specimens. Second column is the specimen thickness. The next columns are the Buffer values for 24 hour, 96 hour and “long” cycle time (a square wave with minimum 7 days settling time). “B-static” is the value calculated for complete moisture equilibrium throughout the thickness of the specimen. “Low airflow” indicates that the specimen was tested in a chamber with lower air turbulence, more similar to a typical dwelling. (Adapted from (Padfield and Jensen 2011))

of the effectiveness of the buffering in this arrangement.

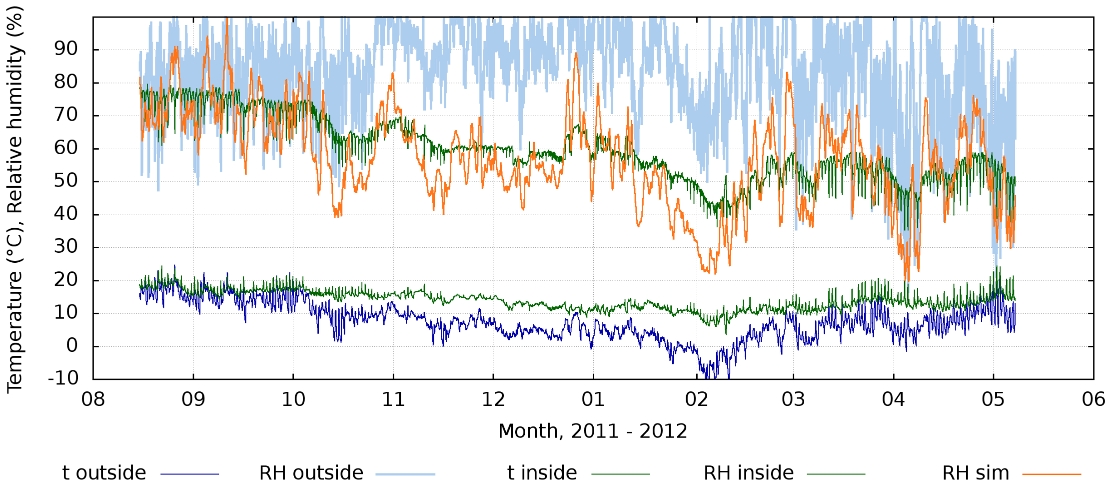


Figure 3.4: The measured climate inside and outside a test room outfitted with humidity buffering, with the predicted climate if the room surfaces were inert to water vapour. From (Padfield, Jensen and Ryhl-Svendsen 2012)

Figure 3.4 shows the results of the measurements. The predicted internal RH is shown in orange, and follows the external RH, though with moderated extremes caused by the low air change rate. In green in shown the actual internal RH level, and the difference is attributed to the buffering capacity of the unfired clay bricks. The effect of the bricks is clear at the medium term, where the buffering is significant. Some high frequency variation remains at the daily scale, likely because the short term response (B-24) is significantly lower than B-long. The buffering is also not very effective at the annual cycle, in this case likely because the total storage potential is not large enough.

3.2.9 Evaporative cooling

Evaporative cooling works by converting sensible heat into latent heat through the phase change of water. As water evaporates the required heat is absorbed from the surrounding air and structures, lowering the ambient temperature. The relationship between relative humidity and dry bulb temperature is shown in figure 3.5. As the moisture content increases though evaporation, the dry bulb temperature decreases at constant wet bulb temperature, indicated as linear, diagonal lines in the diagram.

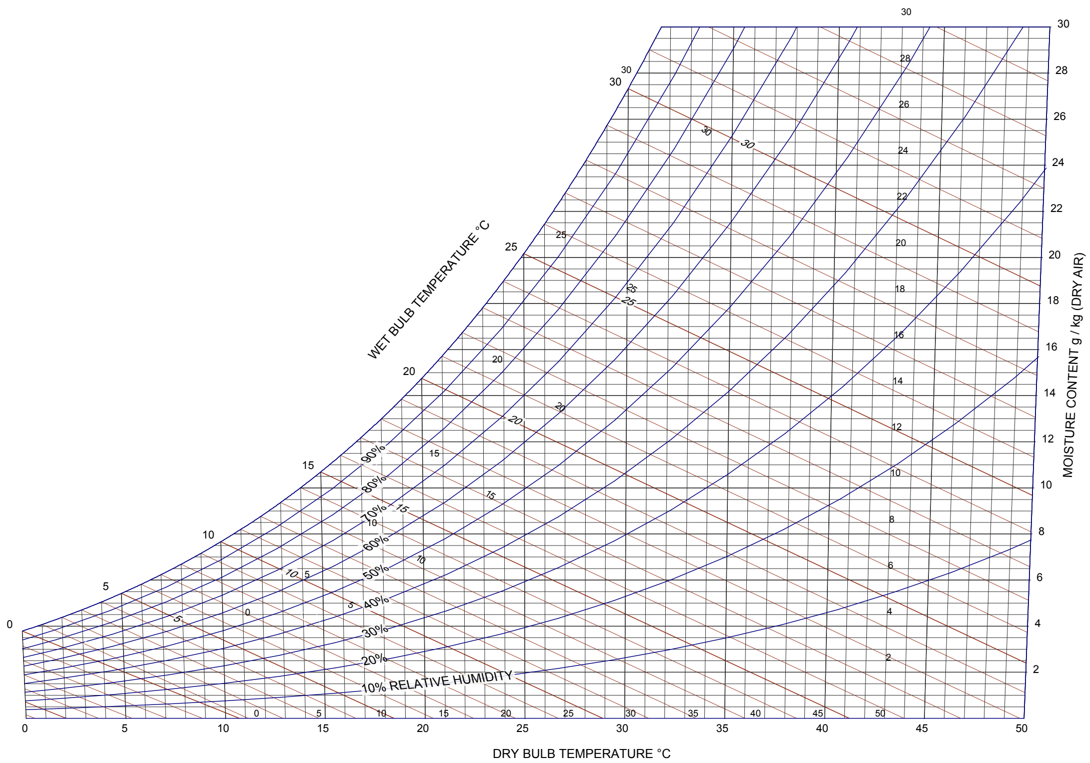


Figure 3.5: Psychrometric chart for normal temperatures at sea level. Adapted from (Givoni 1992).

Table 3.3 indicates the dry and wet bulb temperatures in a number of European cities. The measurements represent the 1st percentile temperature recordings, and typically correspond to hot, mostly sunny days (*Handbook, ASHRAE Fundamentals* 1997), which is the conditions when passive cooling systems are most useful, particularly for domestic dwellings. In all climate conditions, the difference between DBT and WBT is significant which indicates a large potential for evaporative cooling.

The phenomenon is utilised through two different mechanisms, direct evaporative cooling and indirect evaporative cooling. Through the physical principles for the two are the same, the implementation and building consequences can be quite different.

Direct evaporative cooling

Direct evaporative cooling allows water to evaporate into indoor air or inbound ventilation flows, which will decrease the temperature and increase the relative humidity as shown in figure 3.5. This can limit the available cooling potential as the effectiveness of the cooling decreases when the relative humidity, which is a problem particularly in humid climates of when a large cooling effect is required. Because of this the air is often dehumidified before the evaporation takes place through the use of desiccants or by passing it through a membrane (Chan, Riffat and Zhu 2010).

He and Hoyano (2010) have developed a passive evaporative cooling wall meant for outdoor or semi-outdoor spaces which relies on direct evaporative cooling. The wall is constructed from pipes

City	1% DBT (°C)	Mean coincident WBT (°C)	1% WBT (°C)	1% Humidity ratio (g/kg)	1% Dew point temperature (°C)
Glasgow	21.6	16.0	16.7	10.7	15.0
Dublin	20.6	16.3	17.1	11.4	15.9
Oslo (Fernebo)	24.8	16.4	17.4	11.2	15.8
Copenhagen	23.2	16.4	17.4	11.0	15.5
Helsinki	24.1	16.3	17.6	11.4	15.9
Stockholm (Bromma)	24.2	16.2	17.7	11.5	16.1
London (Heathrow)	25.7	17.7	18.7	11.9	16.7
Kaliningrad	25.0	17.7	18.7	12.1	16.9
Oostende	23.0	18.2	18.8	12.5	17.5
Hamburg	25.9	18.0	18.8	12.1	16.9
Munich	27.1	18.0	18.8	12.4	16.4
Zurich	26.4	18.1	18.9	12.8	16.8
La Coruna	23.6	18.2	19.0	12.8	17.7
Amsterdam	24.8	18.1	19.2	12.8	17.8
Berlin	27.9	18.1	19.2	12.1	16.9
Brussels	26.2	18.9	19.8	12.9	17.8
Warsaw	27.0	19.0	19.9	13.0	17.9
Paris (Orly)	28.0	19.4	20.3	13.3	18.2
Santander	24.7	19.4	20.7	14.5	19.7
Milan (Linate)	30.3	22.3	23.5	16.7	21.8

Table 3.3: 1% temperature conditions in European cities (typically hot, sunny summer days). DBT - Dry Bulb temperature, WBT - Wet Bulb Temperature. (Adapted from (*Handbook, ASHRAE Fundamentals* 1997) via (Costelloe and Finn 2003).

of porous ceramics which create capillary forces which pull up water to a height of 1000 mm on the pipes when the lower end is placed in water. As the wind can penetrate the wall made from vertical pipes, the water evaporates and cools the surrounding air.

The ceramics used were composed of cordierite ($Mg_2Al_4Si_5O_{18}$) with a pore volume of 47% and a pore diameter of 5-50 μm. The pores were arranged in a parallel, vertical manner. The pipes had a inner diameter of 28 mm, an outer diameter of 48 mm and a height of 1200 mm. 88 pipes were arranged in 8 offset lines, with a pipe to pipe distance of 58 mm, to form a wall of 600 mm thickness and 1100 mm length.

The cooling wall was tested in Yokohama, Japan, during the summer season (July - September). The daily mean temperature fluctuated between 20°C and 30°C, and the average wind speed was 0.6 m/s. daily mean relative humidity was 76% In the first half of the experiment, the conditions were mainly sunny, while rainy conditions dominated the latter half.

Total evaporation from the wall was measured over a diurnal cycle with sunny conditions. The maximum evaporation was recorded as 2.1 kg / h at 13.00 h, while evaporation stayed over 1.0 kg/h during the full day time. At night, the evaporation was found to vary between 0.3 and 0.6 kg/h.

Air temperatures were measured at the surface of the ceramic rods and at a point 100 mm from the evaporative wall (on the leeward side). A drop of 2°C relative to ambient temperatures was recorded at the 100 mm position, while the temperature of the ceramic surfaces stayed very close to the wet bulb temperature. A cooling efficiency was calculated defined as the ratio of temperature reduction to the difference between ambient dry bulb and wet bulb temperature, i.e. the maximum potential cooling effect from direct evaporative cooling. This ratio was found to fluctuate between 0 and 0.7 at wind speeds below 1.0 m/s, and stabilized around 0.4 when wind speeds exceeded 1.0

m/s.

Givoni (2011) reports on another direct evaporative cooler system, utilizing cooling towers to draw outdoor air into a building. This experiment was set up in Arizona, where the climate allows for great differences between dry bulb and wet bulb temperatures. The cooling tower is of down-fraught design, and fitted with wetted cellulose pads (impregnated with anti-rot salts). Using this system, the incoming air dropped in temperature from 40.6°C to 23.9°C. With a wet bulb ambient temperature of 21.6°C, this represents a cooling efficiency of almost 0.9.

Indirect evaporative cooling

Indirect evaporative cooling involves two air streams between which heat exchange takes place. The streams are separated by a heat conducting wall, with a wet and dry side. The 'working air' passes over the wet side, absorbing vapour and thus cooling the wall. The 'product air' flows over the dry side of the wall which absorbs heat causing the air stream to cool (Chan, Riffat and Zhu 2010). Typically, the roof or ceiling is used as the heat transfer wall.

Indirect evaporative cooling solutions range from very simple systems such as a roof pond (Givoni 2011) or a porous roof which is able to store precipitation (Chan, Riffat and Zhu 2010), to more complex solutions which utilise counterflow heat exchangers between the working air and product air (Costelloe and Finn 2003).

A case reported by Givoni (2011) is tested in Maracaibo, Venezuela. A roof pond is integrated into a four-room dwelling; the pond is covered by a light, insulated and reflective cover and ventilated with outdoor air. The thermal performance of the building was documented over a period ranging from February to September. The maximum outdoor temperature during the period varied between 30°C and 33°C, with a diurnal variation around 4.5°C in the winter and 5.5°C in the summer. The daily average relative humidity was 75%. During the study, the indoor maximum temperatures were consistently 2-3°C below outdoor maximum temperatures, without any increase in indoor humidity.

3.2.10 Conclusions on building ventilation and climate control

It is evident that a large number of strategies exist for regulating the internal climate of buildings, both active and passive. Many passive systems, often vernacular, are able to contribute to the internal climate with less ecological cost or footprint than many contemporary, mechanical-electrical systems. However, it is also evident that demands are increasing, both from regulation and from users. As was seen in the previous chapter, this is in no way limited to developed countries: increasing global prosperity and development are contributing to a increasing demand for internal comfort and health in all regions of the world. In many cases passive or natural solutions are found to be inadequate for modern living standards, which can be explained by lack of performance in some cases, but also by other factors such as perception or expectations, prevailing market momentum, and also unpredictability and complexity of many passive or natural solutions.

Demands on internal climate can be summarised as follows:

- **Thermal comfort** is primarily effected through temperature, but air velocity (higher is desired in a warm environment, lower in a cold environment) and humidity will effect the perception of temperature.

- **Fresh air**. Ventilation is required in order to maintain oxygen levels, and removing pollutants and odours. In most of Europe, 0.5 airchanges per hour is required in dwellings, more in work environments or other places with special needs.
- **Indoor humidity** has a significant effect on occupant health, as well as perceived comfort. In addition, high humidity poses a risk for damages on the building envelope through microbial growth. An ideal range for indoor environments is 40-60%.
- Abundant **daylight** is generally essential for human well-being, but not investigated in this chapter.
- **Spatial Perception**. The building envelope has a direct effect on our senses and how space is perceived through acoustics, vision, and smell. Such qualities are often qualitative rather than quantitative, and have not been investigated in this chapter.

The solutions for passive ventilation which are described in this review are demonstrated to work in many scenarios, but are held back by a number of problems, primarily a lack of capacity and unpredictability/unreliability. Passive systems often depend on favourable wind conditions, which can lead to a fluctuation between over-capacity and under-capacity and associated problems in the form of inability to meet desired ventilation rates and, in the latter case, unnecessary heat loss/gain and high internal air velocities. In addition natural ventilation solutions will often introduce significant design constraints to buildings which employ them and such solutions can be large. This is particularly true if issues of unreliability or capacity are to be addressed. It should also be noted that natural ventilation systems are difficult to combine with heat recovery systems, and few or no such systems are currently on the market.

There are a number of vernacular and contemporary strategies for the active utilisation of thermal mass as a mean to improve thermal comfort and decrease heating and cooling loads. Simple implementations rely on thermal inertia of the building structure to even out extremes of thermal variations, thereby reducing peak loads. Such strategies are particularly effective when the external temperature varies around the desired indoor temperature, but well designed implementations can ameliorate asymmetric thermal loads as well (through night time ventilation or by creating a more even load for the building's heating or cooling system.) Current research investigate thermally activated building systems, where the thermal mass interacts with the HVAC system through water circulation within the building frame and can reduce peak energy usage, but such systems are inflexible and impossible or difficult to adjust during retrofits or refurbishments.

A contemporary development of thermal mass strategies is the use of phase change materials, which can significantly increase the thermal capacity of building materials (by orders of magnitude). As the thermal mass available in a given volume increases significantly, this can allow to use smaller volumes of thermal storage, or it can be utilised to increase the total capacity. In this case a problem arises from the need of creating large energy exchanges between these thermal masses, a problem which is exacerbated by the fact that such materials typically suffer from issues with low heat conductivity, limiting their ability to utilise the increased thermal capacity. This can potentially be addressed through geometric manipulations, but the previous research in this area is limited to very simple geometries that can be readily produced in mass production facilities, and the potential of more complex geometries of the kind which can be achieved with more advanced fabrication capabilities is unexplored.

Finally, another area of study where transient flows could potentially improve current solutions is humidity buffering systems, which tend to be common in vernacular architectures and which is lately gathering interest as a research and development topic. These have the potential to improve indoor climates from a perspective of comfort, occupant health and building health. Existing and currently developed solutions (often using clay based materials or end grain wood) are effective at addressing longer term variations of humidity. However, tests show that short term responsiveness (<24h) is not sufficient to address hour-to-hour variations which often arise from internal (showers, cooking) or external (fog, rain) conditions.

It has also been demonstrated how evaporative cooling can utilise untapped humidity potentials to regulate temperature, particularly if indirect evaporative cooling is used which partly removes the requirement for dry climates.

Many of the systems described here are effective at influencing the interior climate without large use of externally supplied energy. However, they are also prone to be bulky an inflexible, and are typically designed as discrete components to be used as add-ons to architectural designs. Finding methods and systems for integrating similar mechanisms in the building components themselves, while still retaining flexibility and adaptability, is largely unexplored.

In all of these areas we see the need for greater abilities to both control and maximise the exchanges (of enthalpy and mass) taking place across boundaries such as envelopes, between separate air regions, and between solids and air volumes. As shall be seen in the next two sections, transient flows may be a mean of increasing both capacity and control of such exchanges, particularly across shorter distances.

3.3 Fundamentals of mass and heat transfer in transient systems

As has been established in the previous section, manipulation or regulation of the internal climate requires systems which effect mass and energy flows. This is particularly true when it is desirable to minimise the use of external energy: by moving energy around within the building and its immediate surrounding, it is possible to avoid using “distant” energy, e.g. through electric heaters or coolers to compensate for energy losses to the surroundings. Mass transfer (of air) is useful and important in itself (as ventilation), but most often it is as a carrier for heat through convection that mass transfer can lead to energy savings or waste.

This section will address the fundamental mechanisms of mass and heat transfer, with a particular emphasis on turbulence and non-laminar flows.

3.3.1 Heat transfer

Heat is transferred through a number of mechanisms: advection, conduction and radiation. Advection is the bulk movement (as opposed to diffusion) of fluids, and the associated transport of the heat (enthalpy) of the fluid. Conduction (also described as diffusion of heat) is the transfer of heat between objects which are in physical contact, and is governed by Fourier’s Law and the conductivity of the material. *Convection*, which is a more practical term than advection as any fluid systems will simultaneously contain conduction, is defined as the combination of advection and conduction in a fluid. It is generally separated into *forced convection* which is movements of the fluids caused by external forces, and *natural convection* which is caused by internal buoyancy forces arising from the thermal expansion or contraction of the fluid. Radiation is the transfer of heat through electromagnetic radiation. This is always bi-directional, and the radiated heat depends on the temperature of the emitting object. Therefore radiative heat transfer between surfaces of similar temperature tends to cancel out, and radiation plays significant a role only between objects with large temperature differences. The two most significant cases for this is solar heat, and radiation towards space (mostly blocked by clouds which are of a much higher temperature). In addition, devices such as radiators or IR heaters are designed to exploit such phenomena (Lienhard and Lienhard 2015; Hens 2012).

In building design, there is a general ambition to minimise the transfer of heat between the building and its environment. This is primarily achieved by using insulating materials to minimise the transfer across the envelope. Recent developments are also focused on improving the airtightness of the envelope, thus reducing the convective transfer, and these ambitions are increasingly part of contemporary building practice and building codes. The ambition here however, is to look at mechanisms for transfer and storage within and around the building which can be more responsive to variable user needs and external conditions.

Conduction if difficult to vary temporally, as it is dependent on material properties. Convection, however, is strongly influenced by the movement of fluids which can be varied with relative ease. It therefore provides a highly controllable interface for heat transfer.

3.3.2 Mass transfer

The term *mass transfer* indicates “the movement of air, water vapour, water, other gasses, other liquids, and dissolved solids” (Hens 2012). Like heat transfer, mass transfer occurs through mechanisms of diffusion and advection, but unlike heat transfer there is no radiation. The laws governing mass transfer are similar to those governing heat transfer, and they behave similarly, with a notable exception being the properties introduced by the cooling and heating effects of phase changes, and the fact that, contrary to heat, concentrations must *not* be continuous across an interface (Lienhard and Lienhard 2015).

3.3.3 Steady versus transient flows

Transient flows, as opposed to steady state or static flows, are flows where the velocity and pressure change over time. In fluid mechanics, such flows are largely considered a complication (e.g. they can cause complications when dimensioning fluid pipes), and with transience comes rapidly increasing complexity. As a result, many aspects of such flows are not well understood, and explanations are lacking for observed macroscopic as well as microscopic flow patterns (Kle*β*inger, Wunderlich and Bausch 2013).

A subsection of transient flows is turbulent flows. Turbulence, or turbulent flows, is defined as “a spectrum of coexisting vortices in which kinetic energy for the larger ones is dissipated to successively smaller ones until the very smallest of these vortices are damped out by viscous shear stresses” (Lienhard and Lienhard 2015), or “a fluid flow in which the velocity at a given point varies erratically in magnitude and direction.” (Merriam-Webster.com 2015) This differs from laminar flow, where all flow is in the direction of the overall velocity field, and Stokes flow (an extreme case of laminar flow, typically $Re<1$) which is completely reversible (White and Corfield 2006). Turbulence arises in a flow at a transition point which is correlated to the flow’s Reynolds number (Re), or the ratio between the inertial forces and viscous forces. The Re is expressed as:

$$Re = \frac{v \cdot L \cdot \rho}{\mu} \tag{3.1}$$

where L is the length scale, v is the velocity of the flow, ρ the density, and μ the dynamic viscosity of the fluid. Typically the transition to turbulence is found around an *Re* of about 2000 in a straight pipe, but this can be affected by properties such as the local geometry or roughness of the adjacent solid boundaries (White and Corfield 2006; Lienhard and Lienhard 2015). Before the transition to fully turbulent flow, turbulent disturbances appear with an increasing occurrence as the critical *Re*.

If the *Re* is similar between two systems, they can be expected to behave similarly, which is useful when conducting experiments, as it allows for scaling and variation of fluids. This however does not hold for transient flows, where the Womersley number (*Wo*) also needs to be considered. Like the *Re*, it is a product of the Navier Stokes equations, and is calculated through:

$$Wo = L\sqrt{\frac{\omega \cdot \rho}{\mu}} \tag{3.2}$$

where L is the length scale, ω the angular frequency, ρ the density and μ the dynamic viscosity of the fluid (Womersley 1955; Loudon and Tordesillas 1998). Two transient systems are similar if the *Re* as well as the *Wo* are similar.

3.3.4 Transition to turbulence in oscillating flow

A number of studies have been made on the transition to turbulence in oscillating pipe flow (typically bi-directional flow where the average flow is $\neq 0$). These indicate that the critical *Re* is increased over the whole oscillation cycle (Ramaprian and Tu 2006), but that partial turbulence may develop at lower *Re*, either confined to half the oscillation cycle (Merkli and Thomann 2006) or to the boundary layer (Eckmann and Grotberg 2006), while the full-cycle free flow remains laminar. Yellin (1966) notes the importance of the orifice of the pipe as the location where turbulence is created in osillating flow, and further notes that while accelerating flows are more stable than steady flows at a given *Re* in smooth pipes, this is not the case at sources of disturbances where the accelerating flow is instead less stable.

3.3.5 Static vs. dynamic permeability

Flow resistance can be difficult to describe or predict, particularly in a wide range of scenarios ranging from uniform pipes to porous media such as sand, insulation or rock. In pipe flows, the Hagen–Poiseuille equation is typically used (Sutera and Skalak 1993; Bird, Stewart and Lightfoot 2002). This is a simplified law which assume steady state laminar flows and incompressible fluids (at velocities under approximately 100 m/s, air is usually considered incompressible), for turbulent flows the resistance increases relative to the equation solution. The law is:

$$\Delta P = \frac{8 \cdot \mu \cdot L \cdot Q}{\pi \cdot r^4} \tag{3.3}$$

where P is the pressure, μ is dynamic viscosity of the fluid, L is the pipe length of the pipe, and r the radius. From this we can expect that the pressure drop is proportional to the volumetric velocity, and more importantly that replacing a single large diameter pipe with a multitude of small diameter pipes (maintaining the same volumetric flow) will strongly increase the flow resistance, as this increase in pressure drop is proportional to the increase in pipe length and inversely proportional to the pipe radius to the fourth power.

Flow resistance will also increase with increasing tortuosity of the system, so that the pressure drop is proportional to the square of the increase in tortuosity (Epstein 1989). In addition to this effect, the geometric irregularities of a highly tortuous system will promote the formation of turbulence, causing further pressure loss (Lienhard and Lienhard 2015; Bird, Stewart and Lightfoot 2002).

In transient systems where the flow is pulsing or oscillating, the permeability is much more complicated. *Dynamic permeability* (Sheng and Zhou 1988) refers to a demonstrated frequency dependency in permeability of saturated porous media of various micro-structures, and similar phenomena are demonstrated in physiology, e.g. in frequency dependent permeability in lungs (Grimby et al. 1968). As is discussed in greater detail in the next section, Turner and Soar (2008) demonstrate how transient flows of variable frequency penetrates to different depths in the termite mounds, allowing for discriminatory mass transfer mechanisms which can be tuned for spatially varied work.

3.3.6 Boundary layers

As a fluid flows over a solid surface, a boundary layer forms. This is because there is a “no-slip” condition at the interface between the solid and the fluid; the velocity is 0 when the distance from the solid is 0 (Bird, Stewart and Lightfoot 2002). Depending on the velocity of the flow and the viscosity of the fluid, a velocity profile will develop between the stationary fluid at the surface and the free flow. In laminar flow, all particles move parallel to the wall which means that, in combination with the low velocity near the surface, heat transfer will be limited to diffusion (conduction) rates. This also holds for suspended particles or gas concentrations which may interact with the solid surface which will be kept at a distance from the surface. In turbulent layers there is abundant movement in the directions perpendicular to the solid surfaces, causing a strong increase of heat (and mass) transfer between the solid and the fluid (Bird, Stewart and Lightfoot 2002, p 155).

The drag subjected to the fluid flow is dependent on the nature of the boundary layer, where a turbulent layer lads to an increase in drag (Bird, Stewart and Lightfoot 2002). In combination with the tube diameter effects described above this means that properties which cause increased exchange between the flow and the solids it passes through/over will also create increased resistance to said flow, imposing a limit on how effective the exchange can be using continuous flow.

3.3.7 Turbulent mixing

In a turbulent volume of fluid, mixing will take place through two mechanisms: At a larger scale molecules are carried through convection in the form of the multitude of eddies at variable scale; as smaller scale molecules move through diffusion. This can be described through the *eddy diffusivity*, a value which depends not only on the fluid properties, but also on the nature of the flow field (Bird, Stewart and Lightfoot 2002). Eddy diffusivity behaves according to similar laws as diffusion, but is much faster , and ambient fluid from non-turbulent zones will be strongly entrained into a turbulent flow (White and Corfield 2006).

3.3.8 Conclusions on mass and heat transfer in transient systems

From the literature described in this section, it is evident that transient and turbulent flows are of great importance when considering transfer of mass and heat between solids and fluids. Laminar flows, while efficient in that they exhibit less pressure loss compared to turbulent non-0 net flow and are predictable, but will form a boundary layer which prevents exchanges with solids. In addition, flows which have a non-0 average velocity will encounter exponentially increasing flow resistance when taken through high surface area passages which exhibit high tortuosity and narrow channels, which can place another hard limit on the potential solid-fluid exchange.

There are further suggestions that transient flows can be 'tuned' to a particular geometric network, where the properties of the tunnel network (such as edge length and tunnel diameter) can promote or discourage the penetration of oscillating flows of specific wavelength/frequency.

3.4 Termite mound ventilation

The investigations of this thesis are concerned with the large, sub-Saharan termite mounds, and their mechanisms for mediating the relationships and airflows between the colony and the surrounding environment. It is proposed that these mounds can provide a model for architectural envelopes which will enable such envelopes to perform better with less reliance on external energy. This section presents the state of the art of biological research in the mechanisms which regulate air flow in termite mounds.

Fungus growing (also known as mound building) termites of the subfamily Macrotemitinae have long been a fascinating topic of research, and from an engineering perspective it is mostly the ventilation mechanisms found in the impressive mounds and subterranean nests than have been of interest (though the mound morphogenesis as a model for agent based design and self-organization is increasingly attracting the interest of architects and computer scientists). This is also the case in this thesis, where the complex geometry of the mound is examined as a potential model for functional, digitally fabricated building components that may provide a novel approach to building envelope design and function. The termite mounds investigated here are of the species *Macrotermes michaelseni*, though a lot of earlier studies have been made on the related species *Macrotermes bellicosus* as can be seen in the section *Models for Gas Exchange: Continuous Flow.* While these termites are different, particularly in the functional specifics of their mounds, they demonstrate an evolution of our understanding of termite physiology as expressed in the mounds, and the findings in *M michaelseni* highlight the inadequacies of the simple models previously used to describe other species as well.

In this section follows, after a brief introduction to termite physiology, a description of the geometry and morphology of the mounds built by *M michaelseni* and the extensive mapping and documentation that has been done in the TERMES project. This is followed by a historic summary of the continuous flow models that have dominated our interpretations of termite mound function since the 50's and 60's, mostly based on research into *M bellicoss.* Finally, the findings in *M michaelseni* which have challanged these static models are presented, along with an emerging model of transient ventilation modes which are the foundation of the research carried out in this thesis.

3.4.1 Why a termite mound needs to "breathe"

Macrotermes michaelseni are mound-building termites of the subfamily macrotermitinae found in sub-Saharan Africa. These termites are common in many tropical regions of the world, and are a significant part of the ecosystem. In the tropics of Africa, Asian and Oceania they are major contributors to the decomposition of dead vegetable material, releasing the nutrients back to the soil (Aanen et al. 2002). In Namibia where the studies were carried out, *M michaelseni* is one of four occurring species of Macrotermes with a combined typical density of one to four colonies per hectare. They are found in almost all of the country except the most arid desert regions with less than 200 mm of annual rainfall (Turner 2000a). The termites form colonies where all individuals originate from a single pair of alates, and which live within a subterranean nest. The termite population is divided into castes, including the imagoes (queen and king), the workers (minor and major) and the soldiers (minor and major) (Noirot 1969), each carrying out a specific set of functions for the colony, mainly reproduction, foraging, nest and mound maintenance, and defence (with the workers having the least specific role.)

In addition to the differentiated castes, macrotermite colonies live in symbiotic relationships with fungus of the genus *Termitomyces* which they cultivate in order to break down the vegetable matter they harvest, such as dead grass and wood. The fungus is found in and around the nest in special fungus gardens, where the fungus grown on a substrate deposited by the termites in so called fungus combs. The fungus is responsible for most of the metabolic activity of the mound; in a colony it is usual to find several million termites and a significantly larger mass of fungus. Together they consume and produce significant quantities of metabolic gasses, equivalent of a large mammal (Turner 2005). The gas outflow from a nest may be as high as 100,000-400,000 litres per day, out of which 800-1500 litres are CO_2 (Darlington et al. 1997). These flows have to be accommodated all the while maintaining an internal climate which is significantly different than the surrounding air, with lower O_2 concentrations, higher CO_2 concentrations and very high humidity (Turner 2005).

The solution to this climate control problem is believed to be found in the mound built by *M michaelseni* and other species. This significant structure, reaching a height of several meters, is not the nest of the termites or the fungus, but rather is widely believed to be involved with maintaining the internal climate on the nest, in essence ventilating the nest and enhancing the exchange of respiratory gasses (Turner 2000a; Ruelle 1964; Korb 2003). Turner (2005) even proposes that the mound is acting as a physiological respiratory organ for the termite colony, challenging the conventional boundaries of the individual organism (Turner 2000b).

3.4.2 Architecture and morphology of *M michaelseni* mounds

The morphologies of the mounds of various species of termite vary significantly from a physiological perspective, and thus the ventilatory or respiratory mechanisms involved (Lüscher 1961; Korb 2003; Turner 2001). The mounds and mechanisms primarily studied in this thesis are of the species *Macrotermes michaelseni*, and the following section describes the morphology of those mounds. The termite colonies described are all documented near the town of Outjo in Namibia, as described by Turner (2000a). The surrounding habitat is characterised as mopane savanna, a flat landscape of sandy red soil and frequent *Colophospermum mopane* intermixed with other trees.

The mound is typically formed from three distinct parts: a cone shaped base, topped by a more cylindrical spire and surrounded by a pediment formed by outwash from the base and spire. Some mounds are positioned near trees close enough to give significant shade, and some mounds are formed around trees. Mounds sampled by Turner (2000a) were found to be an average 2.16 m

Figure 3.6: Typical *M michaelseni* mound in the research area.

high (0.7-3.85 m) and had an estimated average volume of 3.41 m^3 (0.13-19.08 m^3). The spire of the mounds were found to lean towards the north at a mean 19 degrees north, which is essentially the same as the average zenith angle of the sun throughout the year.

Within the mound an extensive network of tunnels and conduits are found, connecting to the nest at the base of the mound cone (this sits roughly at ground level), surrounded by fungus gardens where the termites cultivate fungus (figure 3.7f). The tunnels permeate mostly the cone and spire of the mound, and occupy on average 28% of the mound volume (figure 3.7b). Several typical characteristics are notable in the network of channels which is reticulated and highly interconnected: A central chimney, surface conduits running vertically along the surface and complex lateral connections between the two.

The central chimney structure rises up from the top of the nest towards the top of the spire, and is connected laterally to other tunnels and spaces throughout the mound (figure 3.7c). The chimney is formed by channels which pass through the fungus gardens in the perimeter of the nest and merge together upwards to form the chimney (3.7f). Along the outside of the mound runs extensive, vertical surface conduits, which tend to connect to the top of the chimney. These run underneath the surface of the mound, separated from the outside by a thin wall. The wall is often partially penetrated by small egress channels, some of which penetrate to the outside (figure 3.7e). These egress channels are most prevalent in areas of fresh building activity (Turner 2000a).

Mound scanning and visualisation

Extensive work to map the internal geometry of the *M michealseni* mounds was carried out by Soar et al. in the TERMES project, which is documented in Abou-Houly (2010). Two modes of mapping was carried out, one digital resulting in a virtual reconstruction of the mound, and one analogue where the mounds was filled with gypsum and the soil washed away, allowing for photo

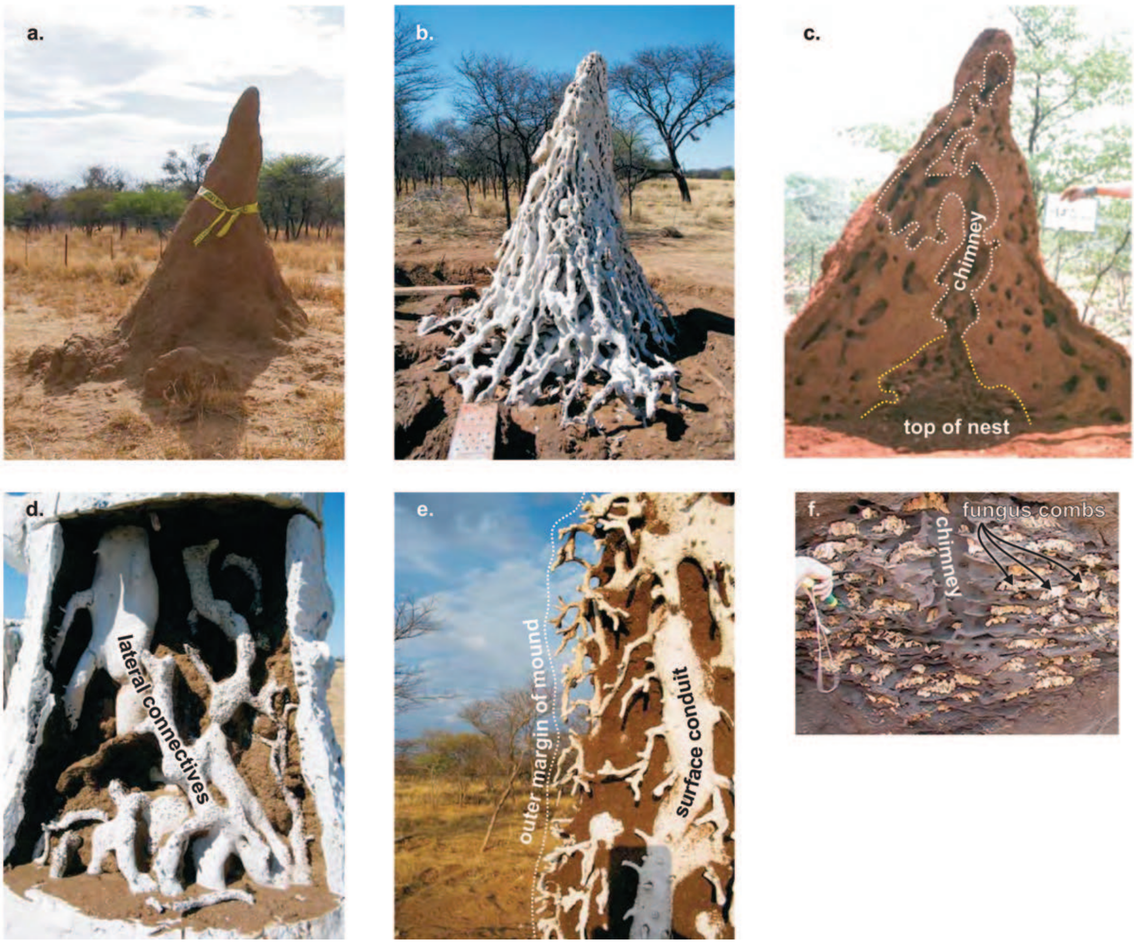


Figure 3.7: Cast of mound internal structure. Adapted from (Turner 2005).

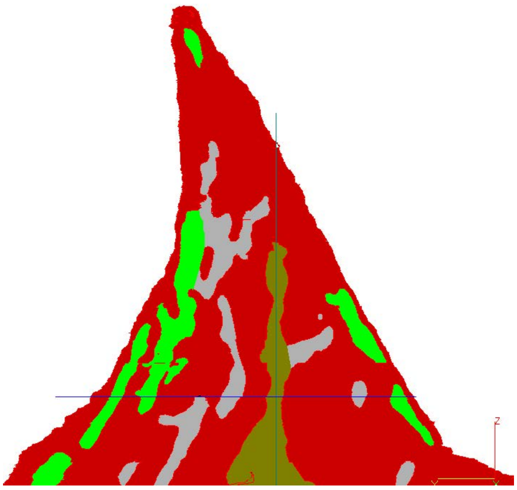
documentation of the internal structures (figure 3.7).

Figure 3.8 shows sections taken from the resulting digital model of the mound. In these the relationship between the central chimney (olive) and the surface conduits (green) are clearly visible. The chimney and conduits merge at the top of the spire, where the conduits are also connected to a highly complex network of narrow egress channels open to the surrounding air. Below the top, the chimney and surface conduits are only connected through lateral connections, shown in grey in the figure.

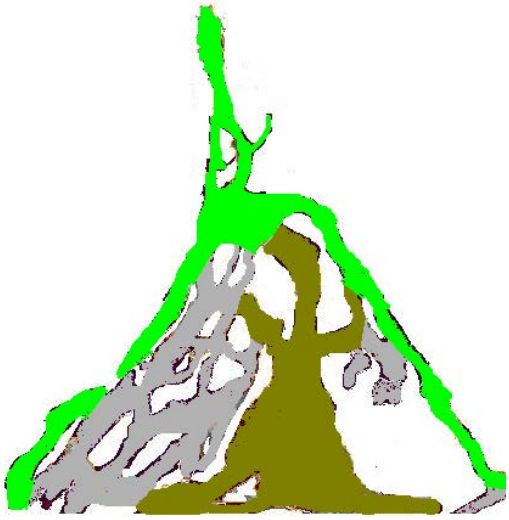
The egress complex sample described in chapter 4 is taken from a location similar to the conditions shown in figure 3.8b, at the left hand (south) side of the spire.

3.4.3 Thermal regulation of termite colonies

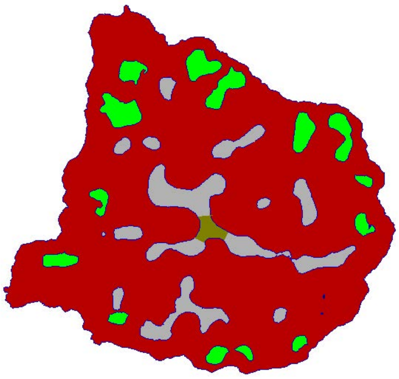
Macrotemitinae ("macrotermites") rely on cultivated fungus to process the food they gather and make the nutrients available for the termites. This has proven to be an incredibly successful symbiosis which has allowed the termites to spread across a large area of the globe and dominate many ecosystems. An explanation for the efficiency of the colonies lies in the specialization of the various parts of the colonies, allowing them to act as a "superorganism" as described above. However, for the *Termitomyces* fungus to have optimal growth conditions they need a temperature near 30°C and a humidity near the saturation point, as well as low CO_2 concentrations (Korb 2003). The termites are known to regulate this temperature, though there appears to be a trade



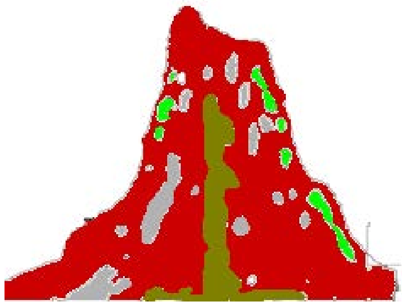
(a) Vertical section 1. Lines indicate the location of horizontal section and vertical section 2.



(b) A vertical section through the negative of the reconstrcuted 3D model, showing the voids only.



(c) Horizontal section (at blue line in vertical section 1)



(d) Vertical section 2 (at green line in vertical section 1)

Figure 3.8: Sections of mound from reconstructed 3d model. Green indicates surface conduits, grey lateral connections and olive the central chimney. Adapted from (Abou-Houly 2010).

off between insulation which maintains a high temperature, and ventilation which tends to lower the temperature.

Korb (2003) has shown that the morphology of the mounds appears to be responsive to external conditions in order to manage this trade off, with the mounds of *Macrotermes bellicosus* taking on different basic structures in the exposed and hot savannah (cathedral-like) and the shaded and cooler rainforest (dome-like). The mounds in the forest exhibit suboptimal conditions with lower temperatures (approximately 28°C) and higher CO_2 concentrations, and operate at lower efficiency. This is also true of small colonies in the savannah, which develop the more complex cathedral shape as the colony grows and metabolic heat generation increases and the CO_2 production goes up. Similarly, the dome-shaped mounds in forested areas develop into complex cathedral mounds when the trees are cut away and external temperature rises.

Ultimately, this trade off would limit the possible habitats for termite colonies as external temperatures drop. While the details of termite thermoregulation are controversial (see for example Turner and Soar (2008)), it suggests that the trade-off issues between ventilation and insulation experienced in engineering are analogous to trade-offs facing the termites.

3.4.4 Models for gas exchange: continuous flow

In 1969, Martin Lüscher published a paper in *Scientific American* outlining measurements which indicated that macro-termites may actively be constructing mounds in such a way that they condition the air (Lüscher 1961), making it more suitable for the termites which cannot survive long in external conditions. He highlights the contradiction between the need to have thick walls which retain the internal heat and moisture, and the supply of fresh air required for respiration.

The model he proposed, which has later become known as the thermosiphon model, was based on measurements in air channels on the inside of ridges along the side of the mounds. In each ridge passed five to ten narrow air channels connecting the cellar below the nest and the top of the mound/nest. The air in the upper parts of the channels had a higher concentration of CO_2 than the air in the lower parts of the passages. Lüscher deduced from this that there was a flow of air through the ridges which had an exchange across the thin layer of mound clay with the surrounding air, acting as the gills of the colony, getting rid of excess CO_2 and replenishing O_2. Based on the production of CO_2 in the nest, he could estimate the air flow rate in the ridge channels to 2 mm per second. The air movement is attributed to convection as hot air generated by metabolic heat causes an upward lift in the nest and a correlating sink as the air is cooled in the ridges. The model is illustrated in figure 3.9, left.

The diffusion across the ridge envelope is presumed to be dependent on the mud being relatively dry, as wet mud is significantly less permeable to gasses. Lüscher notes that the mound envelope dries up quickly after rainfall, partly because rainwater is channelled between the ridges leaving them less saturated. As the investigations took place during the dry season, he speculates that the termites modify or even open up the envelope to the surrounding air during the wet season, when the mud would be less permeable and may not enable enough gas exchange.

Open chimney mounds

Some species of macrotermites have open chimney type mounds, rather than the capped ones Lüscher investigated. These mounds typically have openings at the high point of the mound as well as along the base (Weir 1973). In this case, the circulation is not driven through heat differential

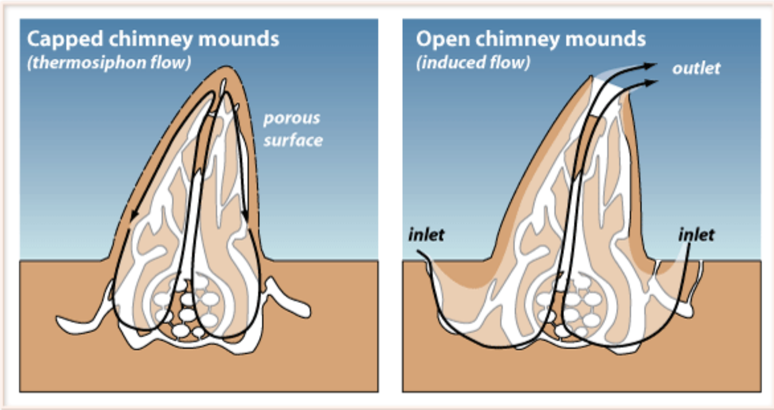


Figure 3.9: Models of continuous flow mound ventilation. Left: thermosiphon flow in capped chimney mounds. Right: Stack effect flow in open chimney mounds. Adapted from (Turner and Soar 2008).

but rather through pressure differentials cased either by varying wind velocity at different altitudes (the boundary layer near the ground decreases velocity) or by the shape of the mound openings (Korb and Linsenmair 2000; Weir 1973). There are multiple mechanisms through which this occurs, but they can be described as stack effect, mostly known as induced flow in biological models (Vogel and Bretz 1972; Turner and Soar 2008). The model is illustrated in figure 3.9, right.

Challenges to thermosiphon model

Korb and Linsenmair (2000) made a series of experiments in order to test the thermosiphon model proposed by Lüscher. Measurements were made in two types of capped chimney mounds of the species *Macrotermes bellicosus*, the cathedral shaped type typically found in savannah habitats and the dome shaped mounds found in forest habitats. The former shares the basic geometry of the mounds tested by Lüscher with thin walls and vertical ridges along the periphery, whereas the dome shaped mounds have thicker walls and a smooth exterior.

The studies concluded that there are two different models of ventilation occurring in the mounds, neither of which corresponds exactly to the previously proposed thermosiphon model. In the cathedral shaped mounds, during the day time the solar heat causes the temperature in the ridge channels to rise above the nest temperatures. This causes the air in the peripheral channels to rise, pulling CO_2 rich air from the nest in to the channels. The steep gradients across the porous wall causes the diffusion rates to increase, introducing fresh air into the mound which is then circulated back into the nest. This is termed externally driven ventilation as the temperature gradients are caused by external sources, i.e. the surrounding air and sun.

During night time, the temperature in the peripheral channels was higher than the surrounding air, but lower than nest temperatures. These conditions seem to be indicative of the thermosiphon model as proposed by Lüscher, as warm air in the nest rises upward where is may exchange gasses with ambient air. However, Korb rises doubts about the viability of the model, as the hot air seems likely to rise up from the nest into the peripheral channels as well, preventing the recirculation of the fresh air back into the nest. This is further illustrated in the dome shaped mounds in the forest habitat, as these lack the peripheral channels which would make a complete circulation difficult to achieve.

Turner (2000b) and Turner (2005) rise another issue with the thermosiphon model: it is based on the premise that the mound needs to be insulated from its surrounding energetic environment. This is a problematic as it interferes with the mechanisms which maintain the homoeostasis of the colony, and limits the feedback loops that seem necessary for the mound to be an adaptive structure.

3.4.5 Evidence of transience

Further investigations of the flows in termite mounds have been carried out by Turner (2001) using bolus release of combustible gasses. His findings, like Korb's, seem to contradict the thermosiphon model, but also go one step further and challenge the assumption of steady, continuous flow as the main mechanism behind mound ventilation, instead finding a transient, or tidal, ventilation regime.

The key insight is that the ventilation is primarily driven by wind, which is almost always turbulent at heights of a few meters. Such wind rapidly changes velocity and direction (see Figure 3.10), and harnessing the full energy spectrum through a static flow device, such as a wind turbine, is not effective as it can only utilise the average velocity.

Turner made measurements of flows within the nest and mound by injecting a bolus of combustible gas at various locations of the nest and mound. By placing sensors throughout the mound to record concentrations over time, it was possible to deduce the internal flows and mixing between various air spaces.

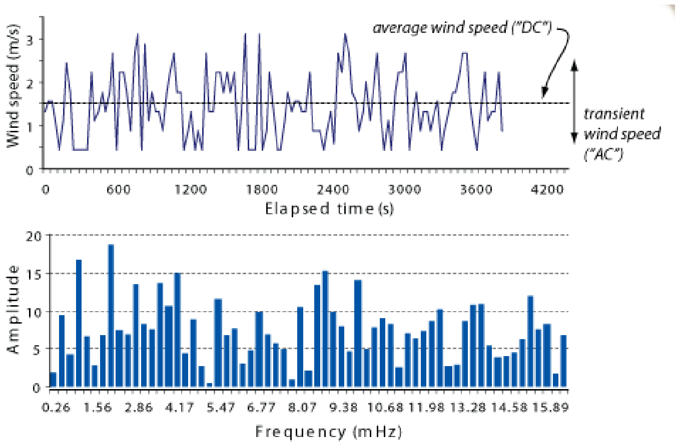


Figure 3.10: Top: Typical natural wind speed. Bottom: Fourier analysis of winds speeds showing broad spectrum of oscillation frequencies found in the wind. Adapted from (Turner 2014a)

Key findings

The main findings were as follows (Turner 2001):

> *The Surface Conduits Constitute at Least One Well-Mixed Air Space That Is Stirred by Wind.* If a bolus of tracer was injected into a surface conduit, the tracer typically migrated rapidly to downwind surface conduits, irrespective of whether tracer was injected. [...] Following other shifts in wind direction ... tracer migrated rapidly to whichever sensor was downwind or lateral to wind. Thus, variations of wind direction induce a “sloshing” movement of air back and forth in the conduits.

Exchange of Gas between the Nest and Mound Surface Is Strongly Influenced by Wind Direction and by Boundary Layer Variation of Wind Speed. The mound experiences strong suction pressures at the downwind and lateral-to-wind surfaces and significant positive pressures at the upwind surface. These pressures affect how gases are distributed in the surface conduits.

Gas Moves Slowly from the Nest to the Surface Conduits. Movement of tracer from the nest to the surface conduits is slow compared to its rapid distribution within the surface conduits.

There is a Two-Way Exchange between the Surface Conduits and Chimney That Is Strongly Damped. Air moves between the surface conduits and chimney through the network of lateral connectives. [...] Thus, there appears to be a hysteresis that favors movements of air from the chimney to the surface conduits but disfavors movements the other way. It is also interesting that the flows of air between chimney and surface conduit are damped considerably compared to movements of gas within the surface conduits themselves. [...] This suggests the reticulated network of lateral connective tunnels serve to damp the movements of air between the chimney and surface conduits.

There Is Little Movement of Tracer Gas from the Surface Conduits Back to the Nest. Circulation of air in the mound should return tracer injected into a surface conduit back to the nest. No such flow was observed.

Air Moves Both Ways between the Chimney and Nest and Is Influenced by Variations of Wind Speed. Tracer moves both from the nest to the chimney and vice versa, but there appears to be a hysteresis in the rates of movement. Tracer moves quickly into the lower chimney from the nest [...] When tracer is injected into the middle chimney ... there is a slight migration of tracer back to the nest [...] During periods of above-average winds, clearance of tracer from the chimney noticeably accelerated.

The Overall Pattern of Air Movements in the Mound Is Highly Complex and Strongly Driven by Wind.

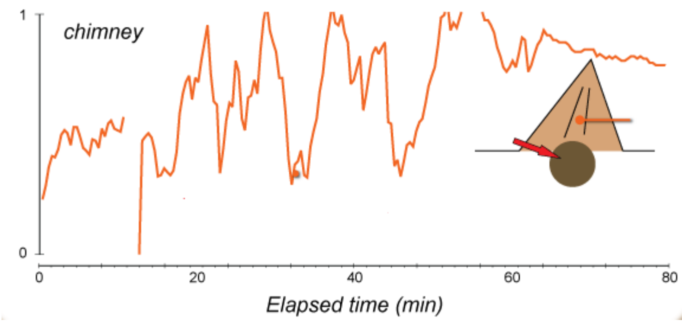


Figure 3.11: Tracer gas injected into nest moves transiently into chimney space. Adapted from (Turner 2001).

From these findings it can be concluded the mass transfer occurring in the mound and which accounts for the transport of metabolic gasses is mainly driven by external energy (though internally driven flows may dominate the nest/chimney interchange), as opposed to the thermosiphon model which relies on internally generated energy. Further, this energy is provided by wind and the transient nature of such winds means that the air movements within the mound are irregular, with a “sloshing” back and forth recorded. There is a significant dampening of the air movements between the outer and inner regions of the mounds, suggesting that the tunnel network act as a filer which allows lower frequency movements further into the nest, while the more rapid movements are contained to the outer regions.

Figure 3.11 illustrates the tidal nature of the mass transfer, where the gas released as a bolus in the nest appears in a periodic and irregular manner in the chimney.

3.4.6 Proposed transient model

Based on the experiments conducted, Turner (2001) draws a number of conclusions regarding the termite colony’s gas exchange:

> Three conclusions follow from the results reported here. First, thermosiphon ventilation does not operate in the mounds and nests of *Macrotermes michaelseni.* Rather, the colony’s gas exchange is driven by a complex interaction between architecture of the mound and nest, kinetic energy in wind, and metabolism-induced natural convection within the nest. Second, ventilatory movements of air in the mound and nest are tidal, not circulatory, and are driven by temporal variation in wind speed and direction. Third, metabolism-induced natural convection is not a significant force driving bulk flows in the mound. It may, however, play a significant role in the mechanisms that underlie homeostasis of the nest’s atmosphere.

The findings show that the thermosiphon model is not an accurate description of the gas exchange processes in M. michealsini colonies, but they also indicate that wind is the primary driver rather than sun as proposed by Korb and Linsenmair (2000)

The model proposed by Turner can be described as a multi-phase model, where various zones within the mound are dominated by different convection regimes. These zones are described in figure 3.12, and are roughly categorized as follows: *Egress tunnels and surface conduits.* In these areas strong wind-driven convection, and specifically the high frequency components of the turbulent spectrum dominates. The *reticulum* is effected by a combination of forced convection driven primarily by the medium frequency components of the turbulent wind spectrum, and natural convection (warm air rising upwards from the nest into the chimney). The equipoise point where the forces of wind induced forced convection and metabolism driven natural convection are balanced appears in the middle chimney, leaving the reticulum likely dominated by medium frequency forced convection. Finally the *nest, lower chimney and subterranean tunnels* are dominated by natural convection, but likely also influenced by low frequency forced convection (Turner 2001; Turner and Soar 2008).

Turbulence and frequency filtering

As has been mentioned above, the transient ventilation in *M. michaelseni* mounds rely on temporal variation of wind speed and direction. This temporal variation is found in turbulent flow, where the component vectors are highly variable in all directions including those perpendicular to the prevailing wind. All wind is turbulent to some degree, which is increased by interaction with geometric obstacles, but the conditions found around the termite mounds may as well be particularly chaotic because of the conditions caused by significant ground heating and associated convective flows (Turner 2001).

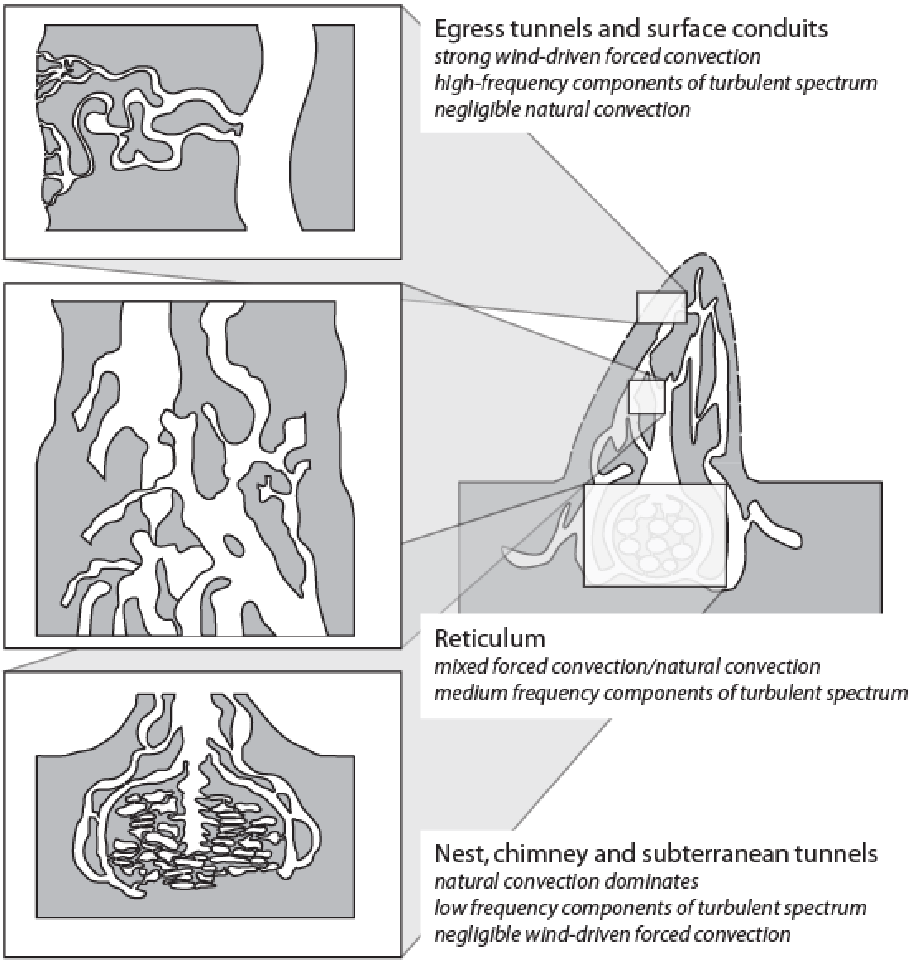


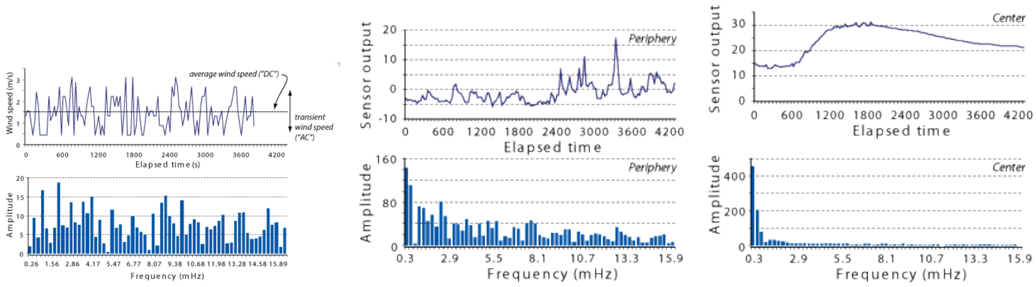
Figure 3.12: Functional organisation of termite mound. Adapted from (Turner and Soar 2008).

As is shown in figure 3.10, the energy found in turbulent wind can be described as a distribution of frequencies, obtained by Fourier analysis. When these frequencies were tracked within the mound geometry a filtering effect was documented, where the rapid variability of wind flows was gradually decreased whereas the slower, lower frequency variations penetrated deeper into the mound. This is visible in the Fourier analysis shown in figure 3.13 which demonstrates the gradual cut-off of higher frequencies while the lower remain.

This filtering of higher frequencies may coincide with the scale of the channel network found within the mound, which is visible in figure 3.7, as the smallest channels are found in the egress tunnels which are exposed to the most rapid changes in flow.

3.4.7 Egress complex

The egress tunnels which connect the surface conduits to the surrounding air are of particular interest to this thesis. These tunnels vary in character over the mound skin and over the year. They are most extensive at the north facing side of the spire, and during the wet season when the colony metabolism is at it's peak (Turner 2000a), suggesting that this structure may be in place to ensure sufficient mass transfer at peak load when the more simple structures are not adequate. At its most extensive state it is a complex network of channels called the "egress complex", and which is described in greater detail in chapter 4. At its least extensive state it is simply a thin



(a) Wind speed **(b)** Mound periphery **(c)** Mound centre

Figure 3.13: Filtering of frequencies in wind turbulence in the termite mound. Image adapted from (Turner 2014b)

wall, which is sometimes partially penetrated by egress tunnels that extend roughly 2/3 of the wall thickness and then end in a dead end (Abou-Houly 2010).

There is little speculation about the nature of the interchange between the surface conduits and the surrounding air, but the assumption is that the quite significant pressures at the surface of the mound force air into or out of the surface conduits. This can happen either through the porous wall that separates the surface conduits from the surrounding air, or the complex egress channels that can be found at the spire of the mound particularly during periods of high metabolic activity (Turner 2000b).

Abou-Houly (2010) investigated the effect of the partially penetrating egress tunnels in the skin of the mound through CFD simulations and smoke experiments, and found that the presence of egress channels increase the flow through the porous wall by a factor of two even when the channels are closed at the surface. This was tested with a constant pressure differential between the inside and outside of the mound skin sample. The CFD analysis also indicated that the closed egress tunnels lead to the formation of a jet of air at the opening of the tunnel, where the velocity of flow was more than an order of magnitude larger than next to the tunnel. Such jetting may contribute to a highly variable and turbulent air flow regime within the surface conduits at high frequencies, particularly when taking into account the high temporal and spatial variation of pressure at the mound surface (Turner 2001).

3.4.8 Conclusions on termite mound ventilation

In this section was outlined the most recent developments of the understanding of the ventilation and mass transfer mechanisms of *M michealseni* colonies. It can be concluded that, for this species, the steady flow models which have previously been thought to drive a static circulation around the nest and mound are wholly or partially incorrect. Instead, a transient ventilation model has been proposed, where the turbulent nature of the wind interacts with the mound's internal reticulated geometry, leading to mass transfer between the nest and the surrounding atmosphere. The mass transfer is significant, as the colony collectively has the metabolic activity of a large mammal, and the nest is separated from the atmosphere by distances of several meters.

In the proposed transient ventilation model, the mound is separated into three intersecting zones, where different mechanisms drive mass transfer. Near the nest, this is likely to be a buoyancy induced circulation, but in the mound, and particularly in the outer periphery of the mound, the mass transfer is likely induced by transient wind events. The fluid dynamics of these interactions is largely unknown, but it is believed that the finer reticulations of the outer zone, the egress complex, is associated with higher frequencies than those which are operational further in in the mound.

It is here proposed that the mass transfer mechanisms of the termite mound could serve as a template for more intelligent utilisation of transient and turbulent flows in buildings, and that these mechanisms could be used to improve on the climate-regulating systems and techniques which are described in the first section of this chapter.

Chapter 4

Transient Mass Transfer Mechanisms

Certainly the building's elements are passive – they do not move or change position – but they can also be seen to be active if their "behaviour" is seen to result in the creation of qualities the world lacks. This is to say, architectural elements are passively active. Seemingly at rest, they are secretly at work. The key is this: in their labour, architectural elements fuse themselves into the latencies of the ambient environment, adopting their capacity for change or movement.

– David Leatherbarrow[1]

4.1 Introduction

The studies conducted in the course of this thesis are focused on the structure known as the egress complex (EC), described in the previous chapter. In this chapter we investigate the mechanisms through which this structure interacts with transient, or more specifically oscillating, airflows through a series of controlled experiments. The egress complex is the outermost part of the termite mounds and forms the first interface between the outside air and the termite colony. It is assumed to have its most important functional role during the periods of peak metabolism, when the colony's need for gas exchange with its outer environment is greatest. This chapter describes the mapping and geometric description of the egress complex, how this structure interacts with transient (more specifically oscillating) airflows in order to generate mass transfer across itself, and

[1] (Leatherbarrow 2009, pp.37-38)

how this interaction is effected by variations of the geometry of the egress complex.

In the mounds of *M. michaelseni* the egress complex is located predominantly on the north facing aspect of the spire and extends part way down the basal cone of the mound. It is effectively the only opening between the mound and the external environment. At normal atmospheric pressures (thus disregarding compression), the only way for outside air to penetrate the internal spaces of the mound is if the pressure varies between the different openings of the egress complex, in which case air will flow in through some channels and flows out through another channel within that face. However, because of the limited size of the EC (approximately 500mm), any wind event with sufficient spatial pressure variation will also exhibit significant temporal variation. It is hypothesised that outside air will penetrate shallowly but quickly reverse direction as the pressure changes across the surface leading to a transient, not continuous flow within the EC and that this transient state may be inducing an enhanced mass transfer across the egress complex.

Based on the model proposed by Turner (2001) and these properties of the egress complex, the following hypotheses were formulated which are tested in this chapter:

A A 0-net, oscillating flow across the egress complex will drive mass transfer across the tunnel network, causing mixing of the air masses on the two sides.

B The topology and geometry of the tunnel network influences the rate of mass transfer achieved. The most important parameters are the reticulation/branching of the topology, and the edge length of the network.

C Large scale (relative to the oscillation amplitude) convection is generated by the oscillations, and is the main driver of the mass transfer.

D Increasing tortuosity and reticulation of the network increases the resistance to steady flows.

E The effects are primarily driven by the interaction of the macro-geometry of the tunnel network, and the material is not a major parameter.

If hypothesis A is correct, this may provide a valuable mechanism for achieving mass and heat transfer without a bulk cross flow. Hypothesis B is based on speculation by Turner and Soar (2008) that the tunnel network is 'tuned' to specific frequencies in the wind which allows them to achieve discriminatory mass transfer, and on the importance of geometric anomalies (orifices, irregularities, curvature) to promote the emergence of turbulence. It was also intended to test if reticulation (bi-directional branching), as is a prominent feature of the egress complex tunnels, was preferable over simple one-directional branching. Hypothesis C was deemed to be the most likely mechanism for mass transport across larger scales. Because of the opacity of the tested panels, these experiments are only partially able to test the hypothesis, and this is revisited in the next chapter. Hypothesis D is a direct extrapolation of current understating of flow resistance in simple pipes to a more complex and irregular network. Finally, to know whether hypothesis E is correct is critical for any engineered implementation of these effects.

These hypotheses are explored thorough the application of an oscillating air column across the egress complex, where the rate of mass transfer is mapped relative to parameters such as amplitude and frequency of the oscillation. The interaction of said oscillations with the geometry of the membrane panel is tested by replacing the EC panel with geometric variations and comparing the mass transfer in the varying iterations. Visualisations of the air flows near the panels are carried out using smoke and a planar laser.

4.2 Methodology

This section describes the experimental set-up used in the investigations documented in this chapter. In 4.2.1 is found an extensive description of the egress complex sample used, where the geometry and topology of the internal tunnel network is mapped. From this mapping was created a number of geometric variations of the EC intended to test the geometric dependence of the mass transfer mechanisms, which are described in 4.2.2. After this follows a description of the experimental apparatus which allowed for the measurement of mass transfer across the different panels and the EC under transient and static conditions. Finally, the experiments conducted using this apparatus are described in 4.2.3.

4.2.1 Egress complex sample - geometry mapping

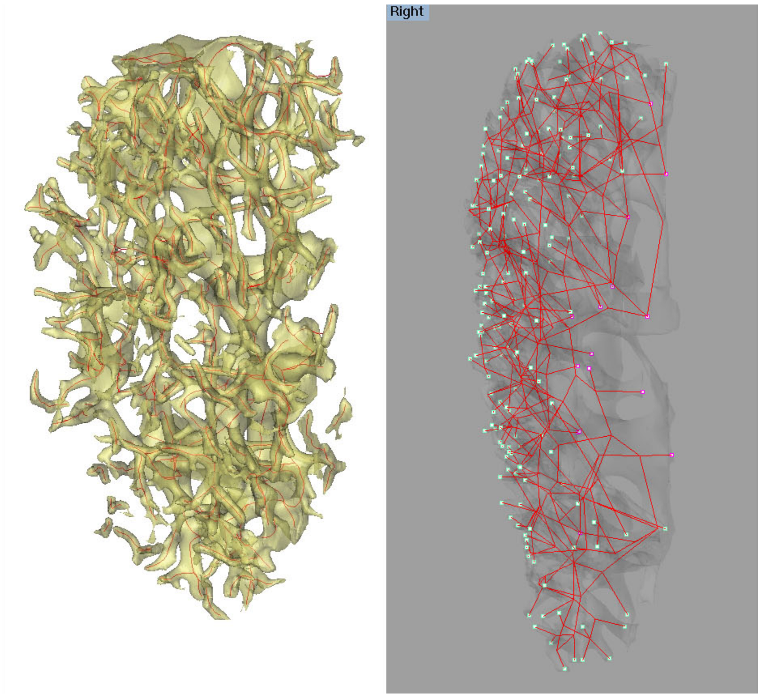
The research undertaken to investigate the nature of the mechanisms involved in this transient system are based on a sample (shown in figure 4.1a), from the egress complex structure of a termite mound from the species *Macrotermes michaelseni* which was retrieved from a study site at the Omatjenne Research Station, near Otjiwarongo, Namibia(Turner 2000a) in February 2005. It was removed from the upper part of the mound's distinctive spire, from the mound's north facing side. The sample was retrieved at a time of year when active modification of the mound exterior is at its peak where Turner describes the open reticulated structure as having an evaporative component to drive a strong water potential through the mound. The sample is typical of a site of active construction in the face of daily rainfall events. The sample was heavily permeated by a gradient of reticulated channels, varying in cross section, length and number, with fewer large (≈15-25 mm Ø) channels towards the interior and more frequent smaller (≈3-5 mm Ø) channels penetrating the exterior surface. To understand and quantify the relationship and connectivity of nodes and edges within this network, the sample was digitally scanned using computer tomography (CT) at Nottingham University Hospital. CT scanning was set to 0.5 mm slice thickness from which a surface approximation was generated from the Dicom data.

The data was processed using Mimics Innovation Suite software in order to quantify and analyse the characteristics of the geometry. From the software was obtained a basic centre-line trace over which a manual trace was made to obtain a node-edge model of the egress complex channel where each node corresponds to an intersection of 2 or more channels (figure 4.1b).

The obtained network was characterised through an analysis of the connectivity and edge length. The results are shown in figure 4.3 and 4.4. For each node, the topological distance (number of edges separating it) from the outer surface and the inner surface conduit was calculated, which allowed the nodes to be sorted into hierarchical categories determined by their hierarchical level relative to the inner and outer openings (level(I) and level(E)). Figures 4.3a, 4.3b and 4.3c show the number of edges connected to each node at level(E) 1, 2 and 3 respectively. Level 0 nodes all have a single edge. Figure 4.3d shows the shortest topological distance to the surface conduits for all the level(E)=0 nodes. Figures 4.4 show the length of edges connected to nodes at level(E) 0-4 respectively.

Overall, the topology of the egress complex is highly interconnected in a reticulated manner. The connections are shorter nearer the outside, and each node has a greater number of neighbours. The channel thickness is inversely correlated, with the channels near the mound surface being the thinnest and the ones near the surface conduits are thicker. The channels are smooth and gently curved, and most are roughly circular in cross section.

(a) Sample from termite mound used for computer tomography (CT) scan.



(b) Inverted CT scan of egress complex sample showing automatic centreline tracing using Mimics software (left) and manually mapped node-edge network (right).

Figure 4.1: Sample of egress complex taken from *Macrotermes michaelseni* mound.

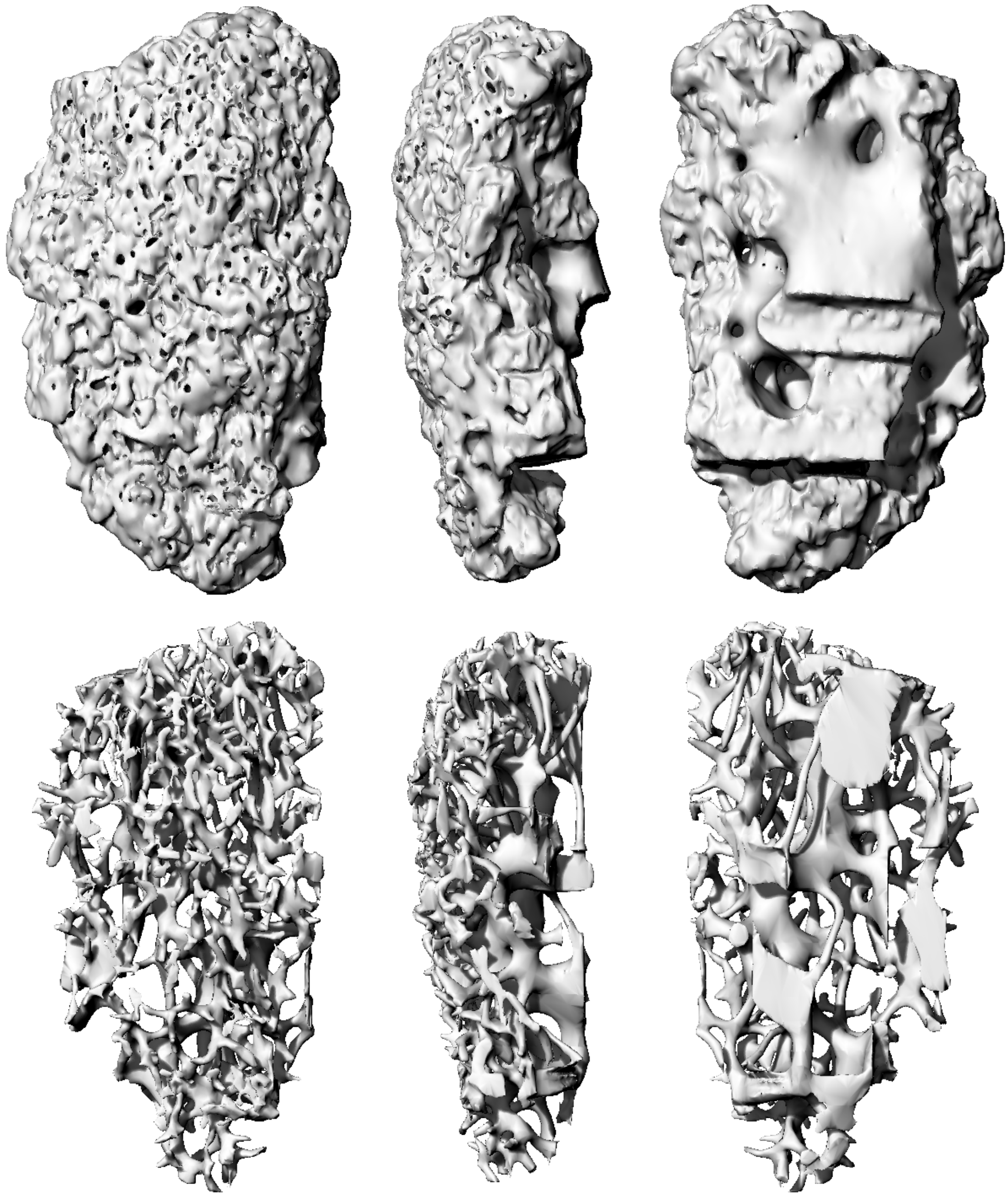


Figure 4.2: Front, left and side view of 3D scan data of sample egress complex. Top: Solid Bottom: Voids

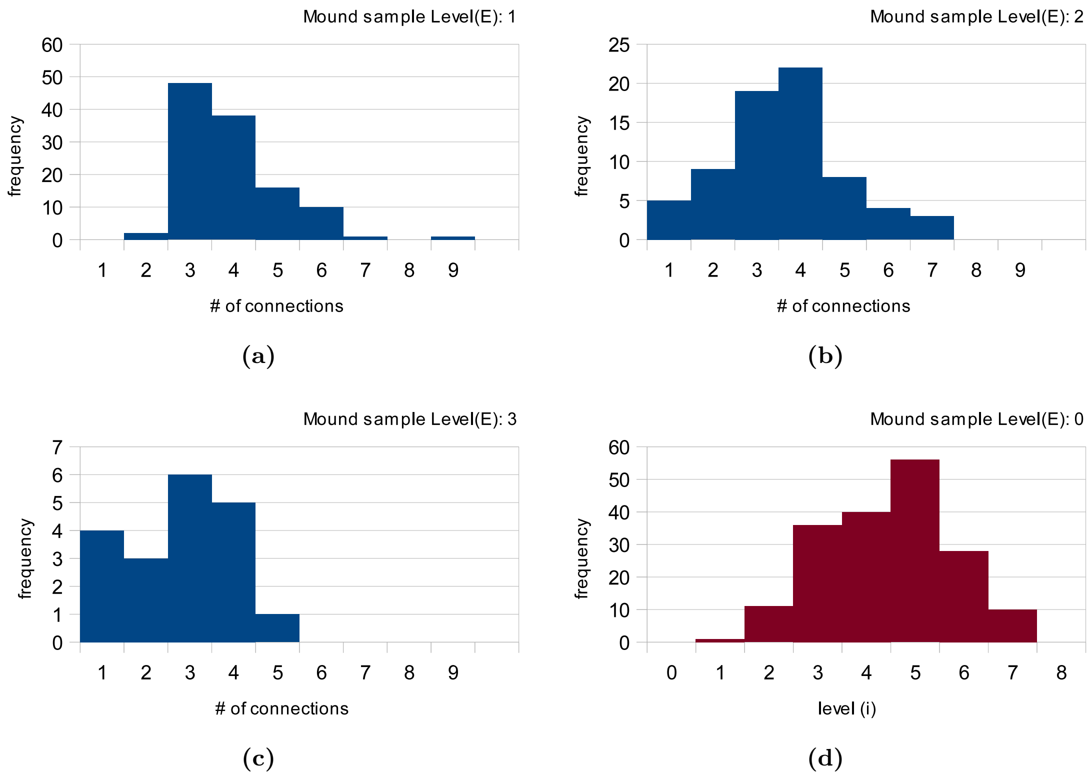


Figure 4.3: A-C: Number of connecting edges in node network of egress complex. D: Number of edges separating outer surface nodes from surface conduits

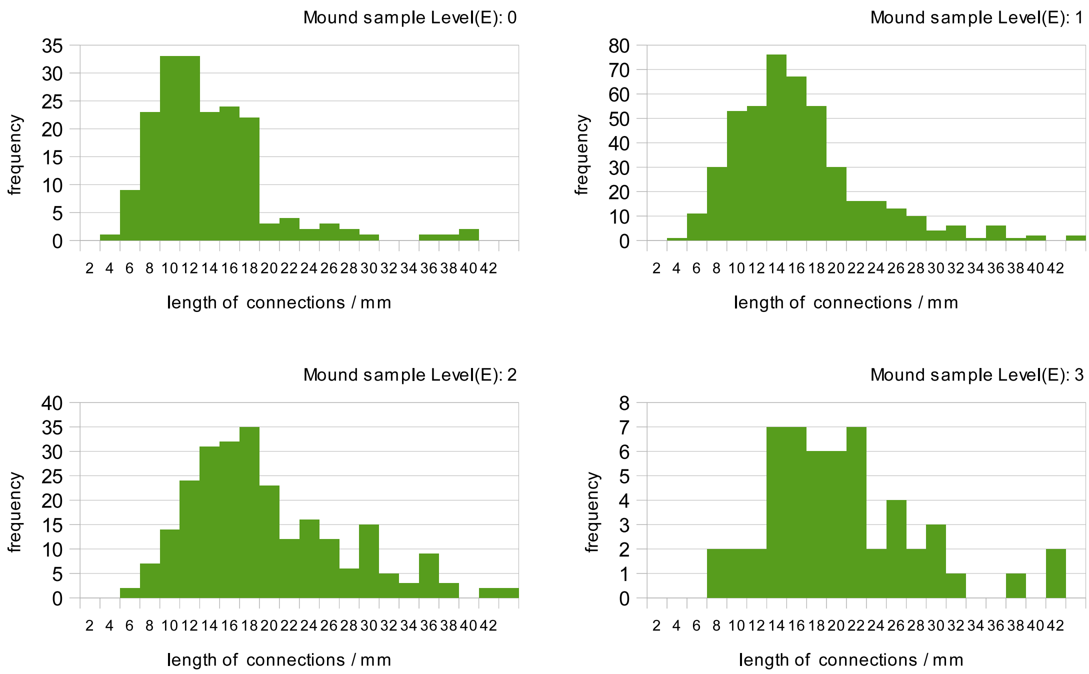


Figure 4.4: Length of connecting edges in node network of egress complex

In the mound, the limits of the egress complex are not clearly defined, but are connected to a similarly reticulated network of channels of which the surface conduits are part (described in greater detail in the previous chapter.)

4.2.2 Geometry variations

In order to determine to what extend this effect is dependent on a specific geometry, and if so what the critical parameters are and how changing them affects the flow and mass transfer, a number of geometric variations were made which emulated the egress complex but with distinct variations of properties.

Three geometric variations of the egress complex were created, each one designed with the intent of testing specific property relating to hypothesis B. Variation A provides a baseline test with 0 reticulation or branching but a similar outer surface and openings, allowing to test if the reticulation/branching contributes to the mass transfer. Variation B has simple branched, non-reticulated topology, which allows to test if the specific EC topology, with its bi-directional reticulation, allows for greater mass transfer. Variation C shares the same nodal network as the EC, but is simplified geometrically, and this enables testing whether any unknown geometric properties (such as curvature and smoothness) contribute to the mass transfer.

The panels were generated using Rhinoceros 3D and fabricated using the same method and material as the printed EC scan: Selective Laser Sintering of nylon powder. All three panels shared a basic outline shape and thickness with the EC as well as the same overall cross sectional area of the channels. The three panel variations are shown in figure 4.5.

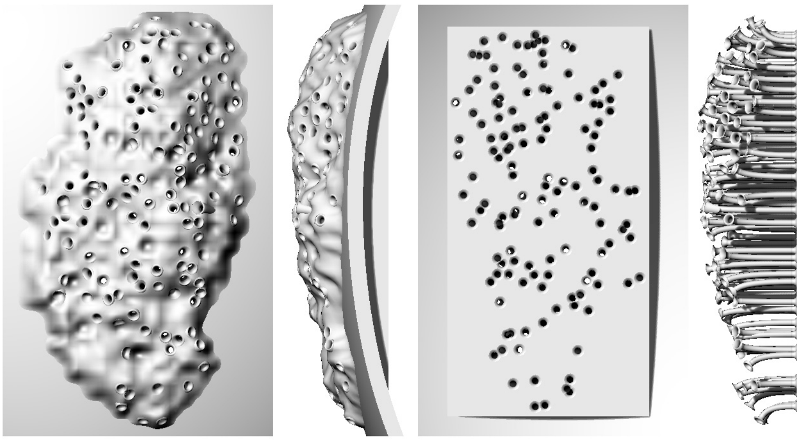
Variant A

This sample (figure 4.5a) has two distinct characteristics. The outer surface is modelled to accurately replicate the egress complex, with a variable, bumpy surface, and with smooth rounding of the orifice edges where the channels meet the surface. This makes it distinct from the two other variants which have a more simplified outer surface and no rounding at orifices or channel intersections. The second defining characteristic is that the channels, while mimicking the EC at the outer surface in position and size, are all unbranched and pass straight to the inner surface with no intersections. In order to compensate for different entrance and exit angles the channels have a gentle curve, but are otherwise straight. The Inner surface therefore has a similar distribution and size of openings to the outer surface.

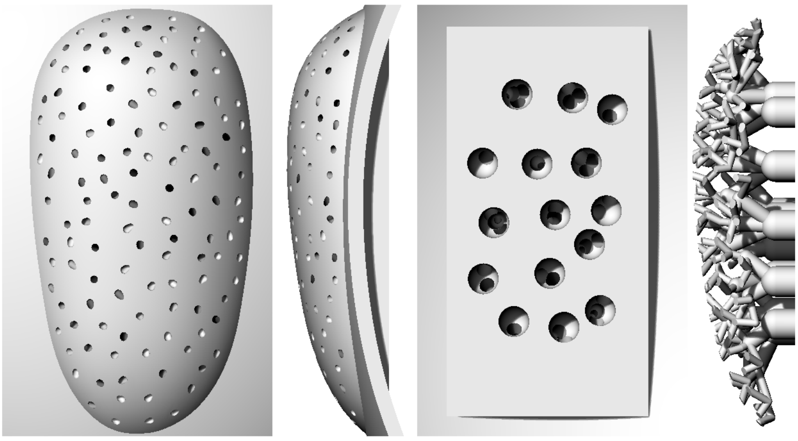
The radius of the tubes was 2 mm with no variation, the average length was 39 mm with a standard deviation of 9.6 mm, and there were 138 tubes. The total tube length of variant 1 was 5,400 mm and the outer surface openings' cross sectional area was 1,700 mm^2.

Variant B

The geometry of this variant is based on a uni-directionally branched, tree-like topology (figure 4.5b). The outer surface is a simplified version relative to the EC or variant A, and all nodes are formed by the intersection of straight tubes with no smoothing or rounding. There were eight trees of branching channels. The 'base' of each tree, which forms an opening on the inner surface of the panel, was 10 mm radius and 12 mm long, node to node. Each base branched into one, two or three smaller branches (level 2.) There were 32 level 2 pipes which were 5 mm radius and with an average length of 29 mm (standard deviation 6.2 mm). Each level 2 branched into 1-4 level 3 branches. There were 64 level 3 pipes which were 2.5 mm radius and with an average length of 19



(a) Variant A; straight perforations without interconnections



(b) Variant B; branching perforations without reticulation

(c) Variant C; Reticulated perforations mapped on node-edge network of original EC sample (see figure 4.1b)

Figure 4.5: Panel variations. From left: front, side, back, voids from side.

mm (standard deviation 6.9 mm). Each level 3 branched into 1-4 level 4 branches, each of which connected to the outer surface. There were 128 level 4 pipes which were 2.5 mm radius and with an average length of 13 mm (standard deviation 2.6 mm). The total length of the pipes in variant 2 was 4000 mm, and the outer surface openings' cross sectional area was 2,500 mm^2.

Variant C

Variant 3 (figure 4.5c) is similar to variant 2, but the channels are tracing the nodes and edges of the EC and are therefore both branched and reticulated. The node-edge model of the EC was obtained by tracing the centrelines of the scanned mesh model in Mimics software for medical imaging. The edges of the network were extruded as straight pipes with the diameter based off measurements of the EC and applied to the pipes in three tiers based on how many nodes removed from the outer surface. The outermost tier radius was 2.5 mm (387 pipes, 159 of which connect to the outer surface) , the middle tier radius was 5 mm (67 pipes), and the inner tier radius was 10 mm (8 pipes) Because the tubes where all straight compared to the curves passages in the EC, the overall tube length was approximately 95% of the EC tube length, for both total and individual tubes, and the meetings and bifurcations were unsmoothed, i.e. sharp. The total length of the pipes in variant 2 was 7,600 mm, and the outer surface openings' cross sectional area was 3,100 mm^2.

Cross sectional area and flow resistance

The total cross sectional area reported above is quite variable, and an initial assumption that these would exhibit greater flows, both in terms of baseline diffusion and a potential steady flow, may seem reasonable. However, these numbers do not necessarily correlate with the minimal cross sectional area (which remains approximately the same for the various panels), as the branching and reticulated geometries have a lower cross sectional area internally, while the straight connections have a constant area.

In order to quantify the flow resistance of the different geometries in relation to hypothesis D, an improvised set up was devised where the panels were mounted to the back chamber, which was in turn connected to a vacuum device which applied a constant suction. The only significant inlet for air into the chamber was through the panel perforations. The resulting pressure in the chamber was measured by attaching a water column to the back chamber. The relative pressures of the back chamber is correlated to the flow resistance of the panel, with a greater pressure difference indicating greater flow resistance.

The EC scan panel and variant A were tested this way, with a recorded pressure of 103 Pa for the (nylon[2]) egress complex and 59 Pa for variant A. We were thus able to conclude that the egress complex presented a significantly greater resistance to steady flows compared to those found in panel A. Testing panels B and C was not relevant as this would have contributed no further understanding relative to the hypothesis.

4.2.3 Experimental apparatus set up

The previously described research (Turner 2001; Turner and Soar 2008) proposes that the mass transfer mechanisms operating in the termite mounds are transient rather than steady. Based on

[2]The clay EC was also tested, and the relative pressure was recorded to 83 Pa. This indicates that the clay/mud has some significant permeability to air flows, if a significant pressure difference is present. This is likely caused by the dried out state of the panel, and a higher moisture content is likely to decrease material permeability.

this proposal a series of experiments were devised to explore if and how a transient system can cause significant mass transfer in situations with zero net steady flow.

We were faced with a challenge in setting up the equipment to characterise the behaviour of an EC structure within a controlled transient state. An unconstrained or open airflow created by an oscillating membrane may produce a continuous cross-flow within the outer surface (top to bottom or side to side) of the connected channels making up the EC, as asymmetries near the membrane can cause a jet which pushes a static flow with an uneven velocity profile towards the EC. Though this may be a factor in driving a respiratory gas potential through the EC, as turbulent eddies flow across the EC's external surface, we wanted to explore the action of a transient flow acting through the EC under controlled conditions.

In order to set up a regularly oscillating air column across the EC, an electronically controlled membrane (in the form of a loudspeaker) was coupled to the 'outer' face of the EC via a chamber consisting of a box to house the EC sample (and subsequent topologically modified EC analogue) and a 1,100 mm length of 100 mm Ø pipe (which housed the speaker) as shown in figure 4.6. The 'inner' face of the EC was coupled to a second sealed chamber (the source chamber) with a 100mm diameter opening. The opening allowed for purging with 7,000 ppm CO_2/air before each run and was covered and sealed with a loose sheet of polymer food protection, during runs, so that the air inside this chamber would oscillate (not compress) freely with the action of the speaker on the other side. It was the concentration of CO_2 in the 'source' chamber which was measured by the CO_2 sensor.

At the amplitudes used in the experiments, the speaker oscillation produced a reasonably laminar oscillating flow through the system (where no obstruction to the flow was present, such as the EC sample). The trade-off was that a fully enclosed system will see a build-up of CO_2 concentration in the outer chamber (connected to the face of the EC which in the mound faced the external environment) which will reduce the accuracy of the measured migration rate across the EC. The addition of the 100mm diameter pipe was intended to mitigate this effect by providing a larger sink for CO_2 moving though the EC.

The speaker gain control was set to drive the air at an amplitude of approximately 5 mm through the channels in the EC, and the speaker output remained constant through the experiment except where the amplitude was stated to be different. Frequencies between 10 Hz and 120 Hz were tested, plus an extended range between 5 Hz and 2,000 Hz where no significant gas exchange took place beyond that demonstrated in the results below.

As the speaker drove the air column across the EC, the concentration of CO_2 in the test chamber was recorded and compared to a baseline gas exchange. The baseline exchange rate was a measure of mass transfer across the EC from the 'source' to the 'sink' where there was no motion (or rather minimal motion as some convection currents will be impossible to eliminate) of the air column, therefore limited to diffusion rates, or an approximation thereof. The decay rate was translated to a theoretical air changes per time unit measurement according to Sherman (1990), which, knowing the volume of the source chamber, can also be expressed as equivalent continuous flow per second. The method for quantifying the air changes assumes a constant concentration in the sink chamber, which was not the case during this experiment and will have led to systematic errors in the rate of gas transfer. This error will always be an underestimation of the mass transfer rates, but as the volumes remain unchanged and the sink chamber was purged between experiments the error is constant between experiments. The sink chamber started at or near atmospheric concentrations

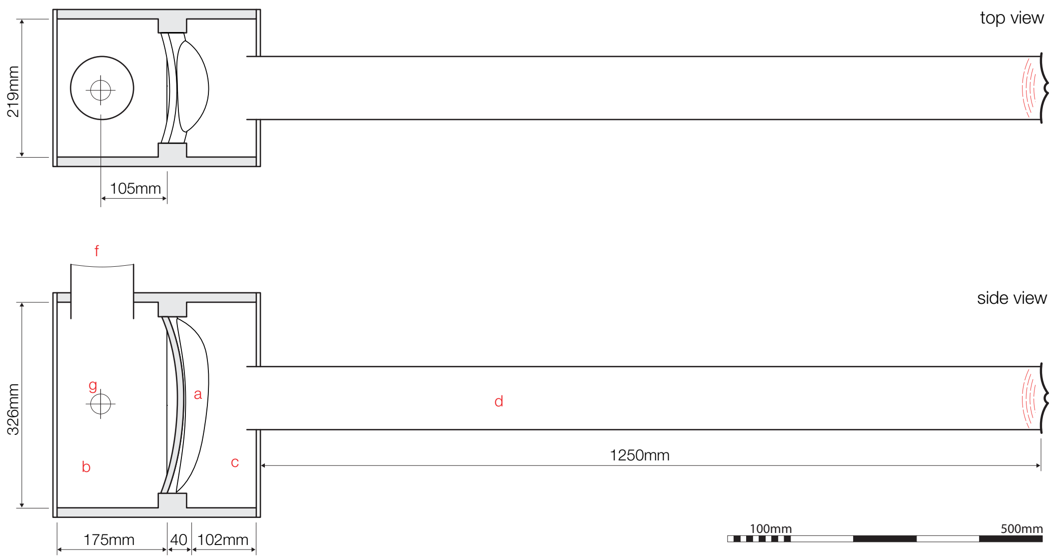


Figure 4.6: Induced oscillations experiment set up. The egress complex (a), was mounted between two boxes (b, c). A pipe (d [diameter 100mm, length 1250mm]) was mounted on the "outside" of the EC, and a speaker (e) was attached to the end of the pipe. On the inside (b), a opening covered by a seal of loose cling-film allowed for air movement as the speaker was active while keeping the outside air from entering the chamber (f). A Cozir Wide Range CO_2 sensor (g) was placed in the middle of the chamber. The volumes of the chambers were: (b) 12.8l, (c) 7.42l, and (d) 9.9l. The thickness of the egress complex is 39 mm on average. The cross section area of the channels at the outside face of the EC is estimated to 1700 mm$\times 10^2$ which increases towards the inner face where the end of the EC is not clearly defined.

(400-700 ppm) for each run, 500 ppm was assumed in calculations.

4.2.4 Experiments conducted

Using the apparatus described, a number of experiments were conducted. These are all listed below.

Oscillation induced mass transfer at varying frequencies

In this primary experiment, the mass transfer rates were measured at variable frequencies, ranging from 10 to 120 Hz (this range was initially larger at the high end, extending to 10,000 Hz, but as no discernible effects were found above 100 Hz these were omitted from the results.) This rate was compared to a base line scenario where the speaker was off and the air in the test chamber was as static as possible.

Amplitude variation

Investigates the effect of variable amplitude oscillations (5 and 10 mm) on the mass transfer rates. *Amplitude* in this text generally refers to displacement amplitude. The amplitude of the oscillations was measured by shining a laser light at the polymer membrane (*f* in figure 4.6), and estimating the vertical displacement of the membrane which is turn could give the volumetric differential.

Resonance effects

To investigate the effect of resonance occurring in the test chamber we made alterations to the volume of the sink chamber and compared the systems in otherwise identical conditions. By varying the length of the pipe to which the speaker was mounted (d in figure 4.6), the resonant characteristics of the sink chamber were modified and the two frequency response profiles were measured.

Material variation

Using the CT scan Dicom data and Mimics for the digital reconstruction of the surfaces, we were able to output the model to a 3D printer. We used a Selective Laser Sintering (SLS) process because it can reproduce complex internal detail at a resolution (<0.5mm) below the CT slice resolution and produce a geometric approximation of the EC, but with a different material – a robust nylon polymer. The EC 3D printed analogue was mounted in the same way as the mound EC and the experiments were repeated for both panels, comparing the resulting mass transfer rates.

Geometry variations

The four different panels described in the beginning of the section (panels A, B, and C in addition to the EC) were all mounted in the apparatus, and the mass transfer rates were measured at oscillation frequencies of 20, 25, 30, 35, and 40 Hz.

Flow visualisation

For the purpose of visualising the flows which were generated during the experiments, a planar laser was used. The back panel of the box mounted to the 'inside' of the EC (position (b) in figure 4.6) was replaced by clear acrylic, and the planar laser was positioned to shine a horisontal plane of light into the chamber through the clear acrylic. A camera was placed at position (f) in figure 4.6 with a field of vision pointing downwards, perpendicular to the laser plane. The measurement chamber was filled with smoke while the sink chamber remained clear, which allowed the flows into the chamber to be visible in the laser plane.

The flows were recorded in two scenarios. In the first, the oscillations were induced at a constant frequency of 50 Hz and a variable amplitude. In the second, the amplitude was kept constant and the frequency was varied (decreasing linearly from 100 Hz to 10 Hz.)

4.3 Results

4.3.1 Oscillation induced mass transfer at varying frequencies

Figure 4.7 shows the CO_2 concentration decay rates under varying oscillation frequencies (the natural logarithm of the CO_2 concentration is plotted against time.) In the baseline or natural diffusion rate experiments, the CO_2 concentration reached 6,000 ppm in approximately 7-800 s (from an initial 7,000 ppm.) Using the methods outlined by Sherman (1990), this is translates to 0.276 air-changes / 1000 s which is equivalent to 3.5×10^{-3} l/s. The strongest response was found around 40 Hz, where the same concentration decrease took approximately 120 s, or an equivalent airflow of 16×10^{-3} l/s. Above 100 Hz and below 10 Hz, the effect of oscillation induced mass transfer was negligible and within the error margin from the measured mass transfer rate at no oscillation.

In figure 4.8, all tested frequencies are presented with the corresponding mass transfer rates.

4.3.2 Amplitude variations and resonance effects

The tests were repeated at an amplitude of 10 mm and were compared to that of 5 mm (Figure 4.9a). There is a considerable effect of amplitude, with a peak mass transfer rate at 50×10^{-3} l/s, roughly four times higher for a doubling of the amplitude. In addition, the peak was wider, giving a stronger effect around a broader spectrum of frequencies and was slightly shifted to higher frequencies (Figure 4.9a).

With the shorter pipe length, the mass transfer constant peaked at higher frequencies as the pipe was longer, which is consistent with a resonance effect (Figure 4.9b).

4.3.3 Study of material variation and properties on dissipation rate

Figure 4.10 shows the response of the mound EC and the SLS analogue with the calculated equivalent air flow rates shown in table 1.

	Panel	
Oscillation	Mound sample	SLS printed analogue
No oscillation:	3.3×10^{-3}	3.6×10^{-3}
40Hz oscillation:	14×10^{-3}	17×10^{-3}

Table 4.1: Material comparison, termite sample vs. SLS sintered nylon analogue. Mass transfer rates in litres per second.

4.3.4 Geometry variations

Figure 4.11 plots the mass transfer rate of the four different panels against frequencies in the range of 20-40 Hz. The peak where greatest mass transfer was observed is found around 30 Hz for all four panels, but the overall rate of mass transfer differed significantly.

While all panels showed significant increase in mass transfer when exposed to the oscillating air, the effect was smaller for variant A and B which reached a peak mass transfer rate of 8.37×10^{-4} l/s and 6.62×10^{-4} l/s, respectively. The peak for the egress complex scan was 10.7×10^{-4} l/s, and for variant C 12.3×10^{-4} l/s. In addition, variant C, as well as to some extent the EC, exhibited a broader peak where the mass transfer rates were almost as high at 25 and 35 Hz as they were at 30 Hz.

4.3.5 Flow visualisations

Figures 4.12 and 4.13 show a sequence of stills from a video recording of a 50 Hz oscillation with variable amplitude. The inner side of the EC is visible in the right hand side of the images, the laser light is shining in from the left. The first still in figure 4.13 is taken at low amplitude oscillations, where no movement was visible in the chamber. The following images show a progression of gradually increasing amplitude at constant frequency, with a time step of approximately 1 s. They show the formation of a jet with a vague associated vortex street emerging from one of the orifices in the egress complex as the amplitude increases.

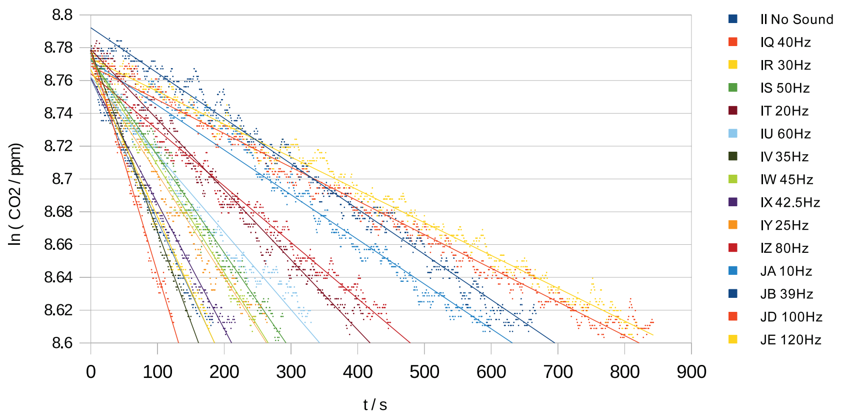


Figure 4.7: Frequency comparison. CO_2 decay under different oscillation frequencies, amplitude constant. Average R^2 equals 0.98.

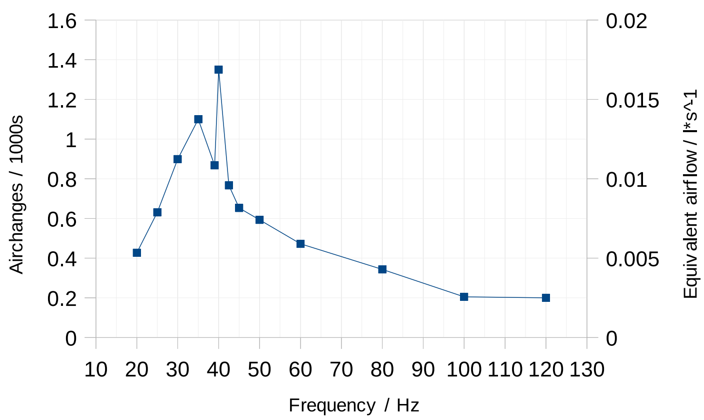
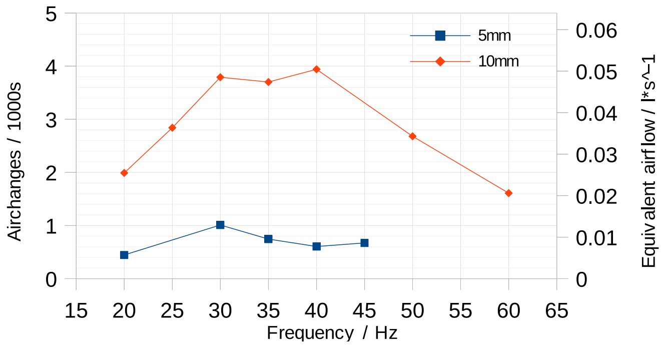
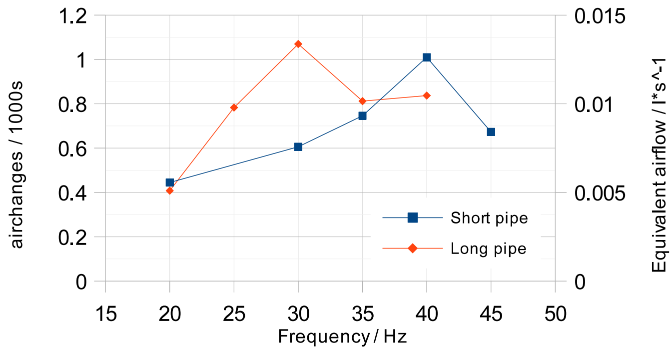


Figure 4.8: Mass transfer rate at different oscillation frequencies calculated from figure 4.7.



(a) Square markers shows original set-up with an oscillation amplitude at approximately 5 mm. Diamond markers show same test with approximately doubled amplitude of the air oscillations.



(b) Square points show original set up with the loud speaker mounted on a long pipe. The diamond points show alternative set up with a shorter pipe.

Figure 4.9: Mass transfer rate profiles across frequencies. Comparison of amplitude depedence and varying chamber resonant characteristics.

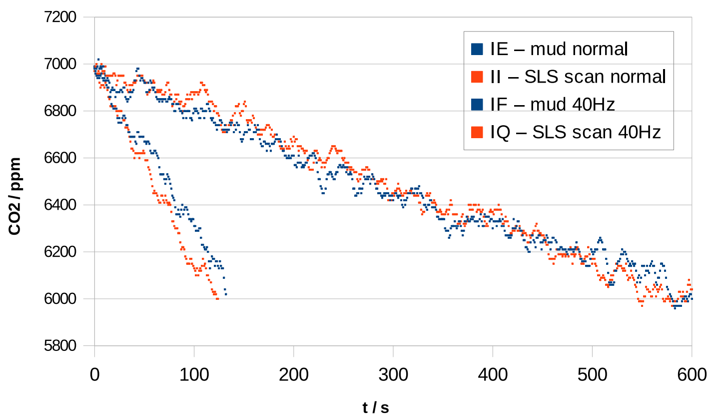


Figure 4.10: Rates of CO_2 concentration decline. Egress complex in mud (from mound) and scanned and printed analogue.

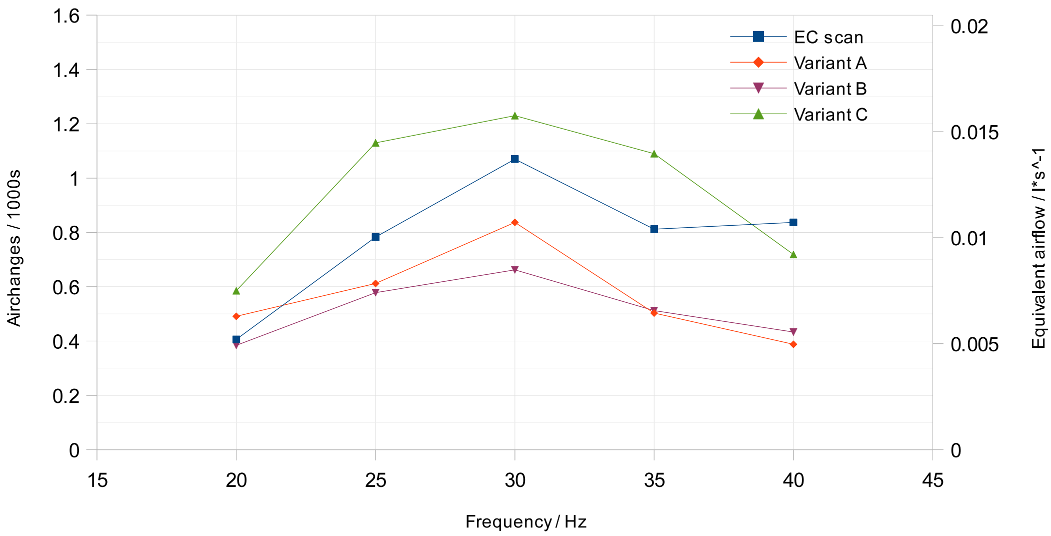


Figure 4.11: Mass transfer rate at different oscillation frequencies for panel variations.

Proceeding from the amplitude variation, the following set-up repeats the experiment with constant amplitude but varying frequency of the oscillations. The laser and camera are in the same positions, but rotated so that the inner surface of the EC is visible in the bottom of the image and the laser light comes from the top. The frequency sweep starts at 100 Hz, proceeding down to 10 Hz. The first still is taken at 88 Hz frequency, and the following images are captured with one second interval, each allowing for a decrease in 1.5 Hz of the frequency. The final image is takes at 58 Hz.

These images do not show a distinct jet forming, but rather a gradually increasing zone of significant turbulence. The zone starts out covering a limited zone in the top right corner of the image, but in the last images, near maximum turbulence, fill the visible space and extend at least 150 mm form the EC surface.

4.4 Interpretation of results

In established models for termite mound mass transfer (Lüscher 1961; Korb 2003), the assumed mechanisms have depended on continuous flow, either through natural or forced convection. Turner has pointed to data that contradict the occurrence of such flows in the mounds of M. michaelseni and suggested an alternative hypothesis where transient flows drive mass transfer (Turner 2001). Here we have found conclusive evidence for such mechanisms: at a range of frequencies a low amplitude oscillation of the air in and around the mound can drive mass transfer of respiratory gasses at rates significantly greater than a purely diffusive system. This corresponds to the region of forced convection in Turner and Soar's three phase model.

Effects of frequency, amplitude and resonance

Transient mass transfer occurs within a range of frequency and amplitude. Within the data there are CO_2 dissipation effects which correlate to the higher frequencies of a net impedance gradient throughout the complete mound structure, as hypothesised by Turner. Within this threshold, a natural distribution emerges with a peak mass transfer around 30-40 Hz, and at the amplitudes tested significant increase over natural diffusion in the range of 10-100 Hz. The exact position of the peak appears to be influenced by the natural resonance of the system, which may indicate that the amplitude and thus movement of the gas molecules is a determining factor of clearance rate over the frequency. We can only speculate about the cause for this peak, but at lower frequencies there is a rapid fall-off in the velocity of the air being moved (assuming constant amplitude), which is likely to reduce the emerging turbulence. The fall-off at higher frequencies is less straight forward to explain, but in these cases the oscillations will propagate as 'acoustic' compression waves with less physical movement of the gas molecules being acted upon, potentially preventing the turbulence from forming. This is possibly supported by the observation that the effect appears to occur at a wider range of frequencies at higher amplitudes.

Geometry over material property

The experiments demonstrate that in the transient mass transfer effects investigated and in this set-up, material properties, structure and material porosity are not significant factors compared to geometry/topology. The mound EC sample has different physical properties from the nylon 3D printed analogue, including a lower resistance to static flows, and greater hygroscopicity, but under identical transient flow conditions, the two exhibited similar mass transfer rates as demonstrated in figure 4.10.

4.4.1 Effects of geometry variations

The results of the variable geometry tests have established that the specific geometry of the panel has a strong effect on its ability to facilitate transient mass transfer of the type examined here. While all geometries exhibited increased rates of mass transfer relative to non-moving systems, only variant C demonstrated rates as high as the egress complex. This panel exhibited rates which were even higher than the EC. A likely explanation for this is the lack of rounding or smoothing. While such characteristics would limit a steady, laminar flow, they are prone to cause greater turbulence. This is exemplified in the formation of synthetic jets which are created by the asymmetry of flow resistance for the in and out stroke across an orifice. The presence of smooth edges will reduce this asymmetry and thus inhibit the formation of large scale flows and turbulence.

Relative to the geometry with unbranched connections (variant A), the increased mass transfer rates of geometry C and the EC are expected, based on the proposed contribution of synthetic jetting or other effects which rely on orifices or intersections. The low rates demonstrated in geometry B are more difficult to explain. They may be a consequence of simply having fewer orifices and intersections, but if this explanation was correct we should expect a mass transfer rate in between geometry A and C, whereas the difference between A and B is much smaller than the difference between B and C. Other potential explanations may reside in the different features of those geometries. One such feature could be the presence of bi-directional branching in EC and C, as opposed to the uni-directional branchings in geometry B, which is relatively general property. It is also possible that there are much more specific features found in the topology and geometry of the egress complex which are fundamental to the transient mass transfer mechanisms. These issues are further explored in the following chapter.

It can further be concluded that the geometric dependence of the transient mass transfer is not correlated to the geometric dependence of mass transfer through steady flows. Rather, it appears that the geometries which have a high resistance to steady flows are the ones which are most prone to facilitate transient mass transfer. In the termite mound, this may function as a filter or shield protecting the homoeostatic balance of the colony while still maintaining the ability for respiratory gas transfer. In potential applications for architectural contexts, this property can contribute significant benefits to transient systems, such as the ability to reduce draughts and gusts while maintaining a constant ventilation flow.

Mass transfer mechanisms

From the visualisation studies it can be concluded that considerable large scale flows are generated from the oscillations. These flows act at spatial scales significantly larger (1-2 orders of magnitude) than the oscillation amplitudes, and extend away from the panels themselves causing mixing in the chambers adjacent to the panels. The flows are turbulent in nature, with distinct eddies forming. Because of the opacity of the panels themselves, it remains unclear whether these flows form within the geometry itself, or if they are only present in the adjacent chambers.

Eddy flows, even if not fully turbulent, result in mixing through the diverging pathways of proximate particles within the turbulent region. These mixing phenomena are typically described at micro scale, though they are effective at larger scales as well (Wiggins and Ottino 2004). Through the resulting turbulence, the diffusion rates in the viscous media is greatly enhanced, and this allows for significant mass transfer even in situations of zero net flow.

In the video recorded during 50 Hz oscillations of the air across the EC at variable amplitude, we can see the formation of a jet around one of the orifices of the EC (figures 4.12, 4.13). This phenomenon is described as synthetic jetting, where “a turbulent jet is synthesized by the interactions of a train of counter-rotating vortex pairs that are formed at the edge of an orifice by the time-periodic motion of a flexible diaphragm in a sealed cavity” (Smith and Glezer 1998). As this jetting phenomenon occurs at any orifice in the presence of an oscillating flow of the right properties, we believe this to be one of the sources of the turbulence driven mixing in the EC. The required properties for a geometric event to drive these jets, to qualify as an ’orifice’, are not clearly defined, but one could speculate that the gradual increase of tunnel diameters within the EC is linked to the jetting, as a certain asymmetry between to spaces are conditional for the formation of the vortexes.

The mechanisms that lead to mixing, via chaotic advection, turbulence or laminar flows, are not conclusively established and the experiments conducted do not provide enough data to rule out any explanation. The following chapter presents further investigations into the nature of these flows and their geometric dependence.

4.5 Conclusions

The data presented in this chapter provide conclusive evidence of transient mass transfer mechanisms which can be driven by an oscillating, 0-net flow air stream across a barrier which is perforated by an intricate network of channels. These findings conform hypotheses presented by Turner (2001) regarding the nature of termite mound respiration, as well as the more specific hypothesis A as proposed at the introduction of this chapter. This suggests that such mechanisms can be generated and exploited in engineering application as is later proposed in chapter 7.

4.5.1 Transient mass transfer

The effects which enhanced the mass transfer rates across the tested panels were observed at frequencies between 10 and 100 Hz, with the greatest effect between 30 and 40 Hz. At lower or higher frequencies the effects were negligible. It was found that the rate of mass transfer was strongly correlated to the amplitude of the oscillations, with a doubling of the amplitude causing a quadruple increase in mass transfer rates, suggesting that the mass transfer rate is proportional to the square of the amplitude. It was also found that increasing the amplitude extended the effective range of frequencies where the transfer rate was the greatest.

Visualisation studies which were performed using a planar laser demonstrated that the oscillations cause turbulence in the chambers adjacent to the panels, confirming hypothesis C. The turbulence was observed to extend into the orifices of the panels, but it was impossible to determine whether the inside of the reticulum was turbulent as the material used for the panels themselves was opaque. Based on the observation of jets forming from the orifices of the panels, it was suggested that synthetic jetting, which is caused by alternating flows over asymmetric openings, plays part in the generation of turbulent flows.

4.5.2 Geometric dependence

The transient mass transfer is strongly influenced by the topological characteristics of the panels as is proposed in hypothesis B. The panels which were generated using a simplified topology of the EC exhibited significant lower rates of mass transfer, while the geometry which was based on the topology of the EC, while not sharing all of the geometric properties such as curvature of channels and smoothness, sustained rates which were similar (in fact slightly greater) to the EC. It is suggested that the reticulation of the EC reticulum is the critical geometric/topological feature, though conclusive evidence for this is not present. What is clear, however, is that increasing branching and reticulation does lead to an increase in mass transfer rates. The experiments also confirm hypothesis E and show that the material is largely irrelevant.

Finally, it was demonstrated that the geometries which presented a stronger barrier against steady flows exhibited the highest rates of transient mass transfer and vice versa, which is in line with what would be expected from predictions based on literature as the tortuosity increases.

Figure 4.12: Still from video showing the formation of a synthetic jet generated by a 50 Hz oscillation. Illuminated by horizontal laser plane and synthetic smoke. Camera placed at (f) in figure 4.6, pointing downwards. Inner edge of panel is visible on the right side of the image.

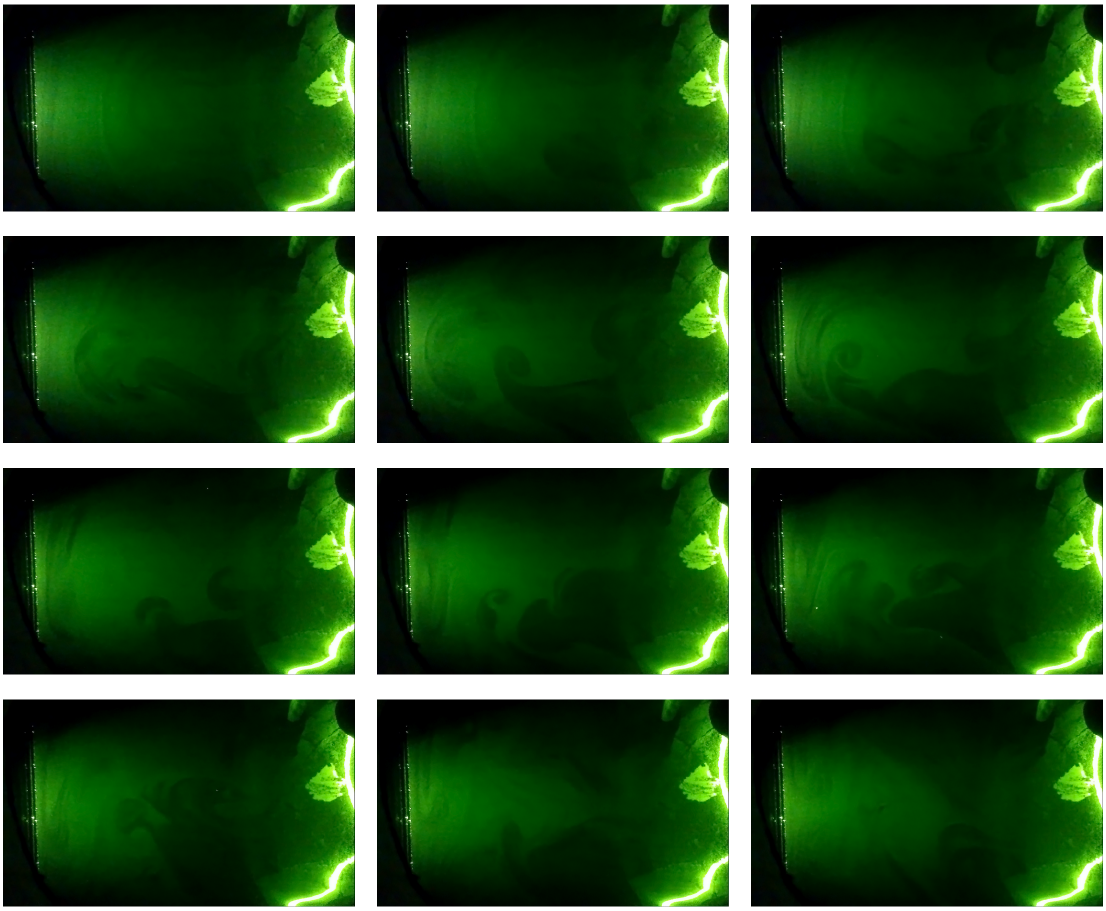


Figure 4.13: Stils at 1 s interval showing formation of synthetic jet with increasing amplitude of 50Hz oscillations. Camera as figure 4.12

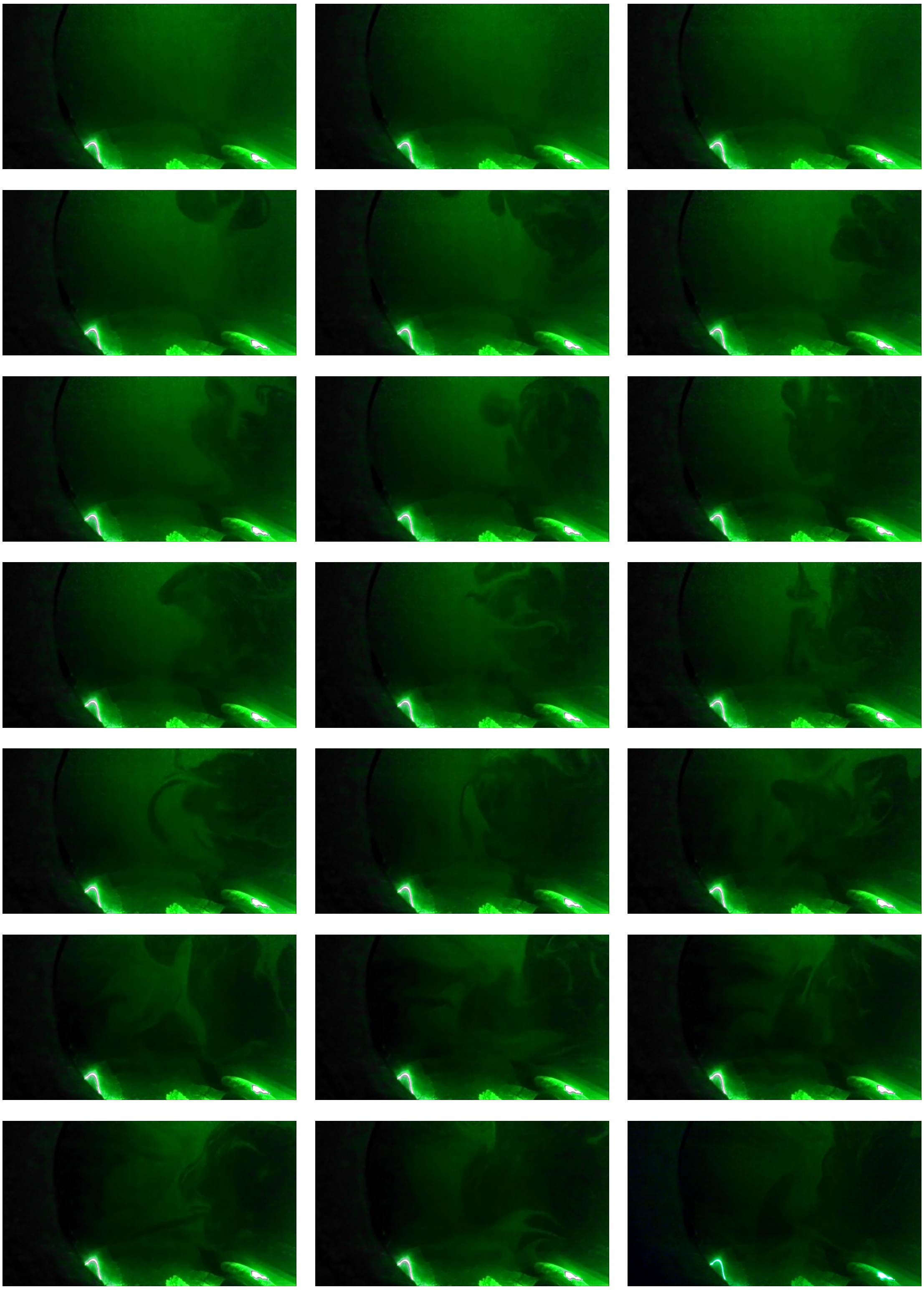


Figure 4.14: Stills at 1 s interval showing formation of turbulence in test chamber with decreasing frequency. First still is taken at 88 Hz, decreasing 1.5 Hz per second, last still at 58 Hz, near maximum turbulence. Illuminated by horizontal laser plane and synthetic smoke. Camera placed at (f) in figure 4.6, pointing downwards. Inner edge of panel is visible on the bottom of the image.

Chapter 5

2-dimensional Measurements of Transient Flow

Big whirls have little whirls,
That feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity.

– Lewis F. Richardson[1]

5.1 Introduction

In the previous chapter was established that oscillating airflows interact with a reticulated tunnel geometry like the one found in the egress complex in a manner which generates significant mass transfer across the channel network. These effects arise for a broad range of network topologies and geometries, but the results indicate that the reticulation of the network creates a stronger mixing than does a simple tree-like branching or unbranched channels. Visualisations using smoke and laser planes suggest that mixing occurs because of turbulence, but the opaque and 3-dimensional nature of the tested panels makes more thorough visualisations impossible. A further complication of the set-up is the large number of parameters in 3-dimensional space, and the practicalities of fabricating and testing multiple samples.

Because of these complications, it was difficult to fully investigate hypothesis B and C using the set-up described in the previous chapter. As is outlined in section 3.3, the nature of the flow is critical in determining how the flow interacts with solids, and the mass and heat transfer properties it exhibits. We therefore introduced a new hypothesis (F): that it is possible to approximate the

[1](Richardson 2007, p. 66)

transient flow over reticulated geometries in a 2-dimensional, simplified analogy, substituting the air for water. This hypothesis is based on Reynolds and Womersley number analysis, suggesting the scalability of the system across different fluids and frequencies. Finally, we hypothesise that and test whether the mass transfer is caused by mixing rather than bulk flow, and therefore is proportional to *Frick's Law* of diffusion, meaning that the mass transfer rates are proportional to the inverse of the distance. In addition, based on the findings in the previous chapter, hypothesis B and C were modified to specify the turbulent nature of the internal flows. The hypotheses investigated in this chapter are thus:

B$_{(B)}$ The topology and geometry of the tunnel network influences the rate of mass transfer achieved *and the characteristics of the flow.* The most important parameters are the reticulation/branching of the topology, and the edge length of the network.

C$_{(B)}$ Large scale (relative to the oscillation amplitude) convection *of a turbulent nature* is generated *within the reticulum* through the the oscillations, and is the main driver of the mass transfer.

F The transient flow observed in the egress complex can be replicated and approximated in 2-dimensional topology using a different fluid (water).

G The mass transfer rates depend on mixing, and are proportional to *Frick's Law* of diffusion.

The 2-dimensional, water-based system has a number of advantages that allow for more detailed investigation of the hypotheses: First is the ability to visualise the internal flow using a video camera. This is aided by the use of water as fluid which can carry a dye acting as a tracer. As the diffusion coefficients of small molecules in water are around 10,000 times smaller than in air (Vogel 1996, p. 199), the mass transfer caused by the induced flow is more distinct relative to background diffusion and easier to measure. The dye used, fluorescein, means the flows can be visualised with high contrast values. The second reason is the reduction of the network complexity, making it easier to isolate geometric and topological changes.

The theoretical underpinning of hypothesis F are explored in section 5.2.1 and the literature review. There may however be additional differences between the two systems which do not relate to the fluid viscosity. These include the increased complexity of the network, which may contribute to the formation of turbulence, or the 3-dimensionality in itself. However, it is worth noting that the experiment is still 3-dimensional (with a similar cross sectional area of the channels), it is only the topology of the network which is 2-dimensional.

5.2 2D experiment set up

The experiment was based on a network geometry with a 2-dimensional topology. In order to facilitate visualisation, water was used as a medium rather than air with fluorescein added to trace flow using a video camera. The scaling effects of using water instead of air are described in the following subsection. Fluorescein ($C_{20}H_{12}O_5$) is a strong dye which glows with a green light when exposed to ultraviolet light (Walker 1987), and which allows for concentrations and flows to be traced in the system.

Figure 5.1 shows how the experiment was set up. A test chamber was created from three layers of transparent acrylic of 5 mm thickness. The middle layer was cut using a laser cutter in order to achieve the desired geometry, with two chambers, (a) and (b) separated by a channels network

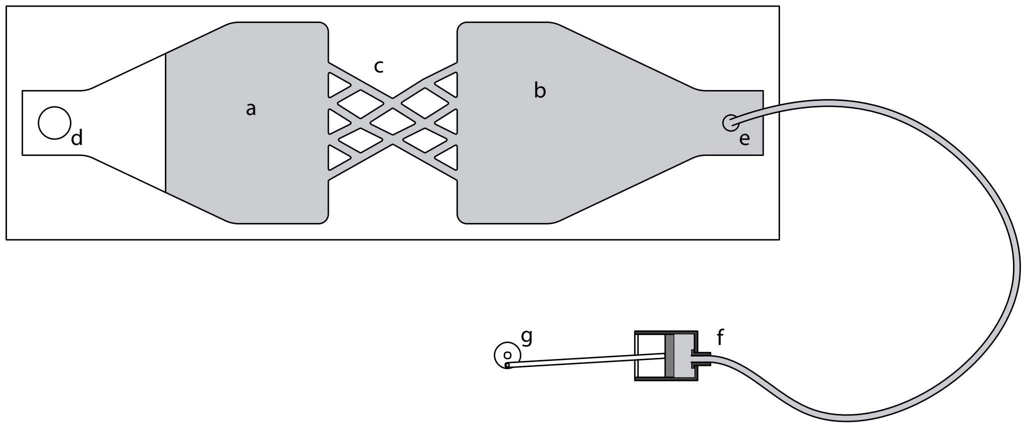


Figure 5.1: Left chamber (a) is open to atmosphere through (d). Right chamber (b) is connected to left chamber through a network of tunnels (c), and to a piston (f) though a tube. Piston is driven from an electric motor (g) at 6Hz.

(c). The chamber placed in horizontal position with the left chamber elevated 5% in order to keep the water-air interface even and on the left chamber, ensuring no air in the channels. The right chamber was connected through a plastic tube (e) to a cylinder and piston (f) driven by an electric motor (g) through a crank arm, which was used to create an oscillating motion in the fluid. The motor operates at a frequency of up to 6 Hz, and a replaceable crankshaft allows for a stroke length of 2 or 4 mm. The cylinder has a diameter of 20 mm. During operation, it was noted that the electric motor and crank arm moved slightly laterally, effectively reducing the amplitude of the oscillations. As a result, the amplitude was measured by tracing a small air bubble placed in the plastic tube (e). The volume of a full stroke was recorded as 0.4 ml for the shorter stroke and 1.2 ml for the longer stroke. The left chamber is connected to the ambient atmosphere, allowing for the unencumbered motion of the fluid in response to the piston movement.

A video/still camera using a CMOS sensor (Olympus OM-D E-M1) was placed above the test chambers, and the different geometries were exposed to varying oscillations as documented below.

5.2.1 Dynamic similarity of water and air

The Womersley number is a dimensionless number used to describe the relationship between oscillating flow frequency and viscous properties of fluids (Loudon and Tordesillas 1998). It is expressed as $\alpha = L(\frac{\omega}{v})^{\frac{1}{2}}$ where α is the Womersley number, ω is the frequency, and v is the kinematic viscosity. In order for similarity between the systems to remain, the Womersley number should be unchanged. For this to be achieved ω and v must be scaled identically. The kinematic viscosity of water at 20^o is $1.00 * 10^{-6}$ whereas the equivalent viscosity of air is $15.1 * 10^{-6}$.

As the peak mass transfer recorded in the previous chapter was found at frequencies around 30 Hz (correlating to a Womersley number of 3.5)[2] this would imply that the peak effect in a water based system should be found at 2Hz. Depending on the relative amplitude of the oscillations the Reynolds number may also contribute to the similarity (or lack of), which may introduce another scaling factor. It was also speculated that the upper effective frequency limit in the air experiment

[2]Interestingly, this is right in between small Wormseley numbers ($\alpha < 1$) where a parabolic velocity profile develops in accordance to Poiseuille's law, and large numbers ($\alpha > 10$), where a plug flow with a square velocity profile forms.

was influenced by the formation of compression waves instead of the molecular displacement found at lower frequencies, and the behaviour of liquid may differ significantly from air in this aspect.

5.2.2 Data analysis method

The behaviour of the fluids was recorded using a video camera. In order to extract measurable data, the image sequence was imported into ImageJ (Abràmoff, Magalhães and Ram 2004) where regions of interest (ROIs) were indicated. These are *left chamber*, *reticulum*, and *right chamber* for the 80 mm wide geometries and *left chamber*, *left reticulum*, *right reticulum*, and *right chamber* for the 160 mm wide geometries. The green channel was isolated in Adobe Photoshop CS5 and the average intensity for each ROI was calculated. The only green light in the scene originated from the excited fluorecein, giving a proxy for fluorecein concentration. The data is then presented in a scatter plot showing the relative dye concentrations for the various ROIs over time.

The mass transfer rate is approximated by measuring the maximum slope of the linearised concentrations over time, analogous to the method used in the previous chapter to calculate flow rate.

5.3 Investigated geometries

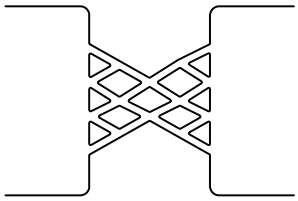
The geometries investigated in this chapter were chosen based on hypothesis $B_{(B)}$ – that the critical characteristic of the tunnel network is the reticulation and edge length – and G which relates to the relationship between mass transfer rates and distance. More specifically, the hypotheses were 1) that any branching causes increased mass transfer, and more branching causes greater mass transfer; 2) that reticulation causes greater mass transfer than simple branching; that node length of the channel network was presumed to affect the mass transfer (literature suggests that certain frequencies or wavelengths are correlated to edge lengths (Turner 2008), we would speculate that amplitude may play a role as well) and; 4), that the mass transfer rates is proportional to *Frick's Law* of diffusion rates (but significantly greater), i.e. that the flow scales to the inverse of the distance. Tunnel dimensions and total panel thickness were based on approximations of the egress complex sample. The geometries tested are shown in figure 5.2, and are described below.

Geometry A: reticulated channels

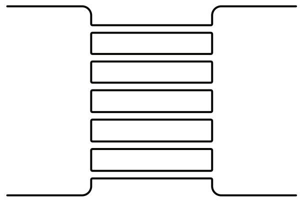
This regular reticulum is the baseline sample, and is constructed from a network of 5 mm wide channels with internal intersections shaped as an 'X'. The overall width is 80 mm, and each side has four openings to the adjacent chamber. The node-to-node length is 23 mm. At the narrowest portion in the centre of the reticulum, the total cross-sectional width is 13 mm over two openings. The maximum cross sectional width is 30 mm. The geometry is shown in figure 5.2a.

Geometry B: straight channels

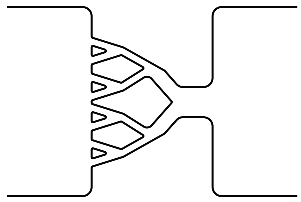
This geometry is constructed from six straight, non-intersecting channels connecting the left chamber to the right. The overall width is 80 mm, as is the individual channel length (equivalent to node-to-node length.) The constant cross-sectional width is 30 mm. The geometry is shown in figure 5.2b. This geometry, together with geometry A, can show whether hypothesis F is likely to be true: in case this system is analogous to the 3-d geometries, we would expect a much greater mass transfer rate in geometry A. If this turns out to be the case, the visualisation potential of



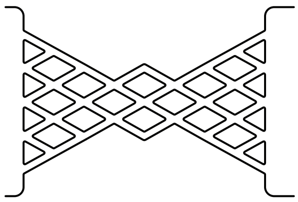
(a) Reticulated channels. Total width 80 mm, edge (node-to-node) length 23 mm, edge count 20.



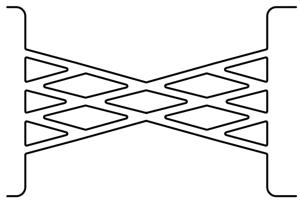
(b) Straight channels. Total width 80 mm, edge (node-to-node) length 80 mm, edge count 6.



(c) Branched, tree-like channels. Total width 80 mm, edge (node-to-node) length 20-30 mm, edge count 15.



(d) Double distance, increased node count. Total width 160 mm, edge (node-to-node) length 23 mm, edge count 44.



(e) Double distance, stretched node topology. Total width 160 mm, edge (node-to-node) length 41 mm, edge count 20.

Figure 5.2: List and description of investigated geometries.

this set-up can be used to characterise the nature of the flow, thus testing the revised hypothesis C.

Geometry C: branched, tree-like channels

This geometry is created from a unidirectional branching giving it a tree-like topology and is modelled on the variant B 3-dimensional geometry in the previous chapter. The overall width is 80 mm, and there are eight openings to the left chamber, each with a 5mm width, and a single opening to the right chamber which is 20 mm. The minimum total cross-sectional width is 20 mm. The geometry is shown in figure 5.2c. It is intended to test the reticulation vs. branching aspect of hypothesis B, but it is worth noting that the difference between reticulated and branched is less clear in the 2-dimensional system, as the lack of a third dimension forces an increased interconnectivity. This may instead, or in addition, provide a mean to study the effect of variable edge length in the network.

Geometry D: double distance, increased node count

This geometry has the double overall width relative to geometry A, 160 mm. The node-to-node distance is identical, but the node and edge count is significantly higher. The minimum cross-sectional width is the same at 13 mm, but the maximum cross sectional width is 40 mm. The geometry is shown in figure 5.2d. This geometry is particularly selected to test hypothesis G and offer insights into how mass transfer scales over a larger distance.

Geometry E: double distance, stretched node topology

The overall width of geometry E is identical to geometry D, but the node topology is identical to geometry A. As a consequently, the node-to-node distance is increased to 41 mm, while the minimum and maximum cross-sectional width is identical to geometry A, 13 mm and 30 mm respectively. The geometry is shown in figure 5.2e. This geometry allows us to test the effect of edge length on the mass transfer, in relation to hypothesis B.

5.4 Frequency variations

Initially geometry A was tested across a range of oscillation frequencies in order to establish if any clear thresholds in mixing effect occurred with respect to frequency, and to establish how the transient mixing scales with frequency. The results are shown in figure 5.4. The first graph (5.4) shows the raw data for the four (four ROIs were used for this analysis in spite of an overall geometry width of 80 mm) ROIs. The second (5.4b) shows the total deviation (for the 4 ROIs) from the overall mean intensity. As the dye approaches perfectly even distribution (complete mixing), this value approaches 0.

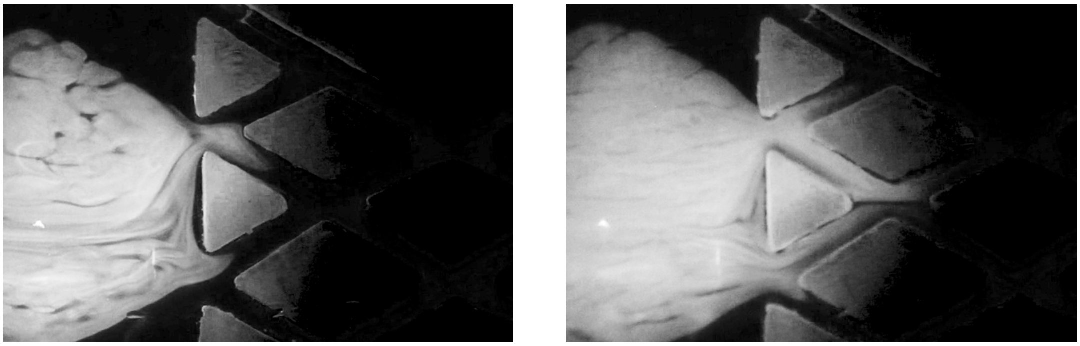
In both of these graphs can be seen a threshold of the mixing rate as the frequency is increased from 4.7 Hz to 6.3 Hz. This coincides with a visual observation of a shift from laminar (where the flow of the left stroke is close to a complete reversal of the right stroke) to turbulent flow (with little or no reversibility between the left and right stroke) in the recorded video.

The Re can be calculated for this threshold to approximately 10^1-10^2, which typically corresponds to a laminar flow (turbulent thresholds are generally found well above 10^3).

When comparing the dynamic similarity of this set up with the 3-dimensional, it was predicted that the maximum mass transfer rate would be found at 2 Hz (corresponding to 30 Hz in the air system previously tested). The results however showed a significant increase above this, and no frequency peak was found. This may indicate that the situation cannot be described based on Womersley numbers alone, but it is also possible that other parameters such as amplitude of oscillations and the geometry translation from 3d to 2d have failed to maintain absolute consistency. We would suggest that a likely explanation of this may be in the relative compressibility of the two fluids. It may be that the decrease of mass transfer rates at higher frequencies in the 3-dimensional, air system was because the formation of compression waves instead of displacement. If so, as water is much less compressible than air, it would be expected that a corresponding drop-off in mass transfer would not be found in the water system.

5.4.1 Static / 0 Hz flow

The set-up was also used to visualise the characteristic of static flow in the investigated geometries. Using the same set up, a slow, steady flow of approximately 1 mm / s was induced in the test chamber. Images of this flow is shown in figure 5.3. These images show how a clear boundary layer forms which is visible as a dark band near the channel walls. This boundary layer also forms between two separate flows (figure 5.3b), preventing mixing at the channel intersection. The boundary layer thickness (in laminar flow) is proportional to the inverse of the square root of the Reynolds number (in turbulent flow to the inverse of $Re^{1/5}$), so Re similarity needs to be maintained between the water and air systems for the boundary layer to be similar (which is the



(a) t = 15 s

(b) t = 37 s

Figure 5.3: Frame captures from video showing static flow at approximately 1 mm / s.

case in these experiments). This also means that the boundary layer is exaggerated in the low flow rates shown here.

5.5 Geometry and amplitude variations

Based on the results of the frequency analysis, the following experiments were carried out at a constant frequency of 6-6.5 Hz, as this was found to most clearly illustrate and achieve the phenomena which are of interest in the study. The various geometries were exposed to oscillations of two different amplitudes, and the results analysed as described using ImageJ.

5.5.1 Mass transfer rates

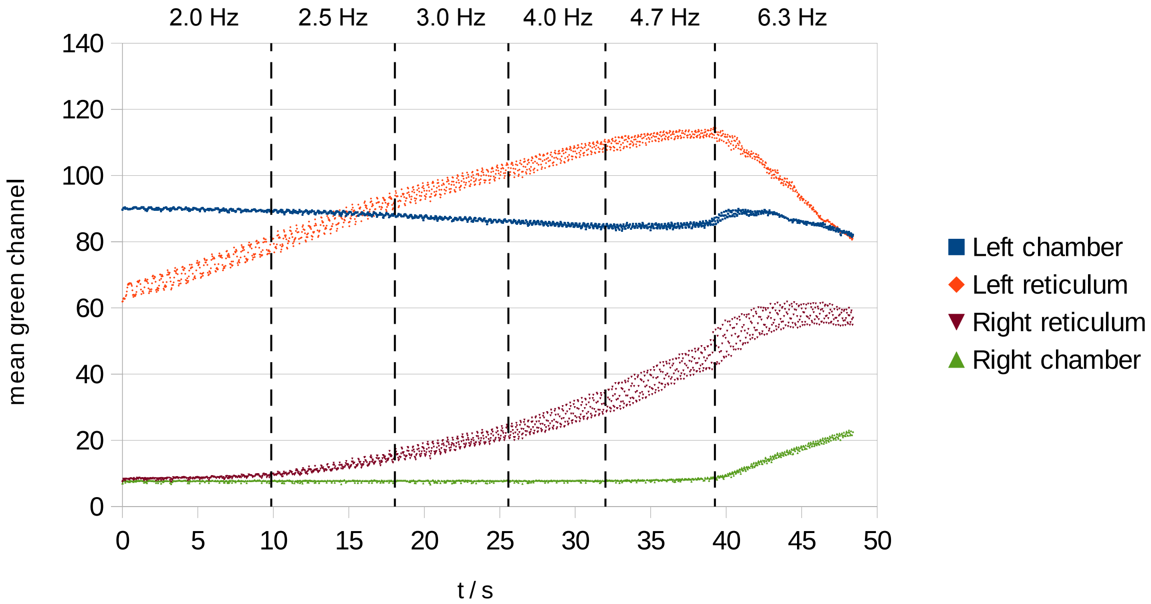
The graphs presented in figure 5.5 show mass transfer in the narrow geometries (A-C), the left column for short strokes and the right column for long strokes. Figure 5.6 shows geometries D and E. Graphs in figure 5.7 show the linearised values for the right chamber in all geometries, with the maximum slope indicated as a line. Table 5.1 collects the slopes from figure 5.7, providing a comparable measure for mass transfer rates[3].

	Stroke amplitude	
Geometry	Short	Long
A:	0.09	0.39
B:	0.01	0.10
C:	0.09	0.14
D:	0.02	0.37
E:	0.01	0.07

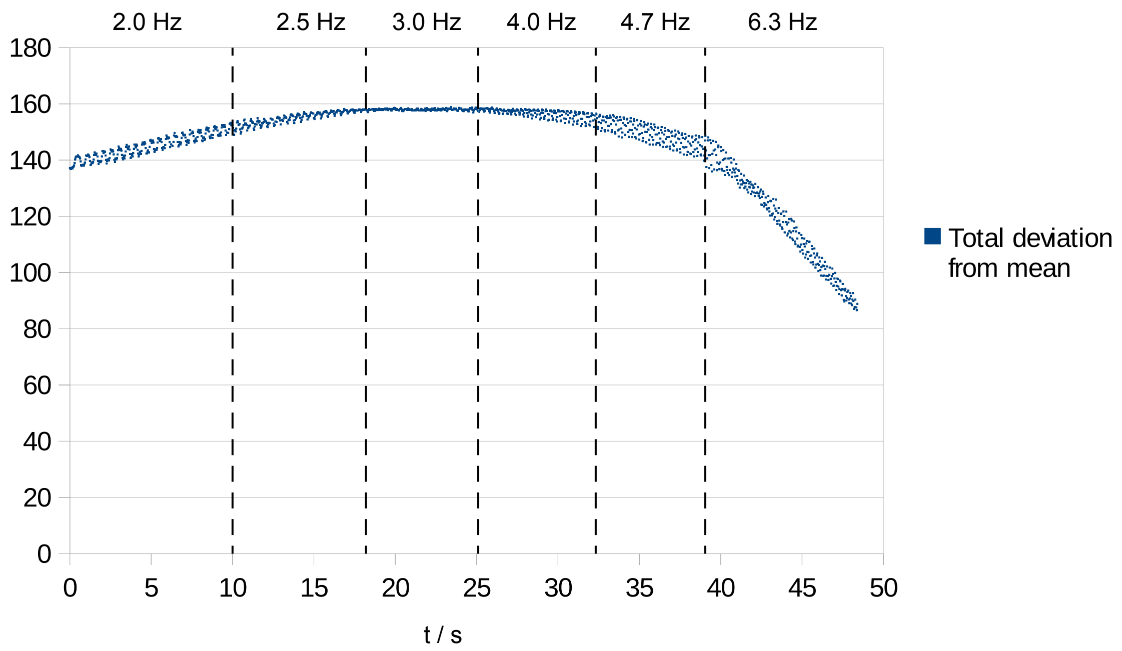
Table 5.1: Rate of change of dye concentration in right chamber. Based on data in figure 5.7.

Geometry A exhibits a significant rate of mass transfer, with a right chamber transfer rate of 0.09 for the low amplitude oscillation and 0.39 for the high amplitude oscillation. With a low

[3]For the experiments with the lowest rates of mass transfer (i.e. the low amplitude experiments with geometries B, D and E) the 60s time period may be too short to accurately capture the maximum slope and the rate may be slightly underestimated.



(a) Analysis of mean intensity (0-256) of green channel in four regions of interest (ROI). Frequency of oscillations indicated at secondary x-axis.



(b) Total deviation form mean grey value of all ROI. Zero deviation equals perfect mixing.

Figure 5.4: Analysis of mixing rate at variable frequency in geometry A.

amplitude oscillation, considerable mixing takes place and some increase of right chamber intensity is clearly visible around 30s. After 60 s the mean intensity in the right chamber has increased 6 units, low but noticeable. With high amplitude oscillations the effect is significantly stronger and the intensity in the right chamber starts increasing after only 5-10 s. The reticulum is quickly saturated with dye, and in less than 10 s the mean intensity has increased 40 units, after which less increase takes place.

With geometry B the results are strikingly different, and very little mass transfer takes place. Using a short stroke, no increase in concentration in the right chamber is recorded (recorded as a transfer rate of 0.01), and barely any in the channels. Even with the large amplitude oscillation the increase in the right chamber is very limited (0.10), though some dye migrates into the channels.

In the tree-like geometry C the mass transfer rates are significantly larger than in geometry B, and similar to the rates observed in geometry A (0.09 for low amplitude and 0.14 for high amplitude). In the case of the short stroke, the concentration increase in the channels is even larger than in geometry A, though the overall rate of increase in the right chamber is smaller. In the long stroke scenario the rates of transfer to the right chamber are significantly smaller than in geometry A. The difference of mass transfer rates between the short and long stroke (0.09 and 0.14 – 50% increase) are very small compared to those observed in geometry A (0.09 and 0.39 – 300% increase).

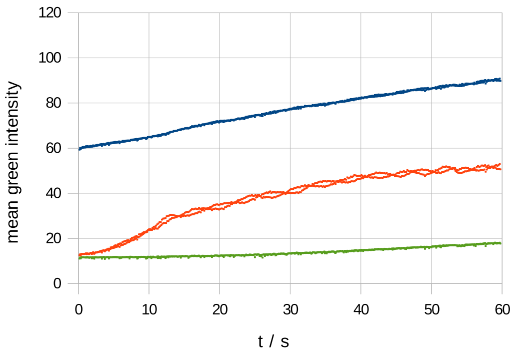
Geometry D, which has a reticulum with double the width relative to geometry A, exhibits significantly lower rates of mass transfer than geometry A (0.02) for the low amplitude oscillation but an almost identical rate for the high amplitude oscillation (0.37). It is worth noting that the maximum cross-sectional width is higher in this geometry relative to geometry A (40 mm instead of 30 mm), which makes the effective oscillation amplitude for part of the reticulum 25% lower. At the same time, the node count per length unit is higher.

Geometry E shares the same overall width as geometry D, but the node-to-node length is increased as the topology remains identical to geometry A. This change was found to have a considerable effect on the mass transfer rates which were lower than geometry D: 0.01 and 0.07 for the low and high amplitude oscillations, respectively (compared to 0.02 and 0.037 for geometry D).

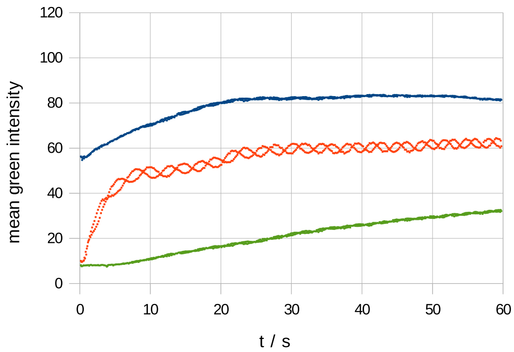
5.5.2 Interpretation of results

The results in the previous section confirm the hypothesis that the geometry/topology of the tunnel network influences the rate of mass transfer (hypothesis B). This is most clearly visible when comparing geometries A and B, and supports the hypothesis that the 2-dimensional topology and water medium can be used to approximate the 3-dimensional system (F). In any static flow, geometry B, with less tortuousity and a greater minimum cross-sectional width, would present less flow resistance and exhibit a greater flow rate. However, in the oscillating flow the mass transfer across this geometry is negligible relative to the flow across the reticulated network in geometry A. In addition, the difference in flow rate between the deeper geometries D and E indicate that node-to-node (edge) distance influences the mass transfer achieved for a given amplitude and frequency of oscillation, with a decreased mass transfer rate following on an increased edge length. It is not clear from the experiments whether there is a minimum edge length for optimum mass transfer.

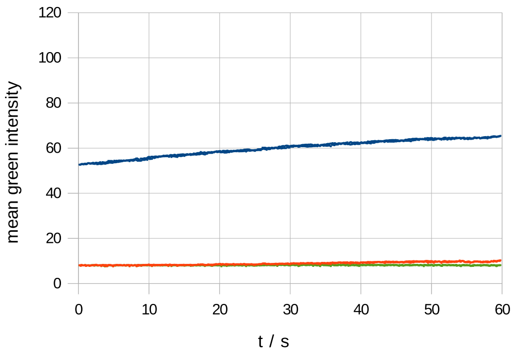
Further the results highlight the strong dependence on amplitude which is consistent with the results from the previous chapter. Analysis of transfer rates across geometries A and D at



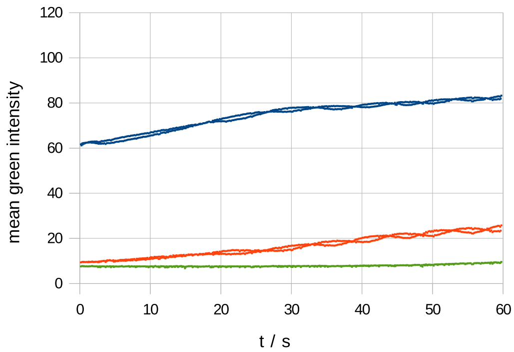
(a) Geometry A - short stroke.



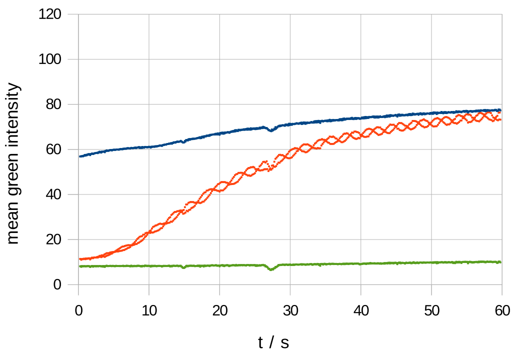
(b) Geometry A - long stroke.



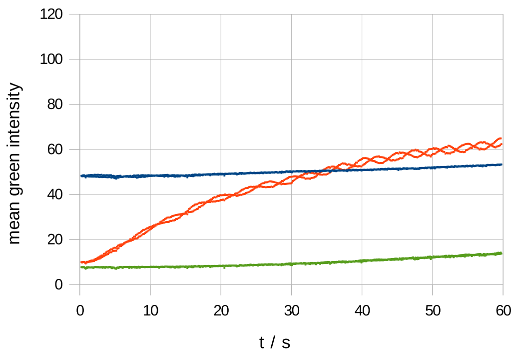
(c) Geometry B - short stroke.



(d) Geometry B - long stroke.

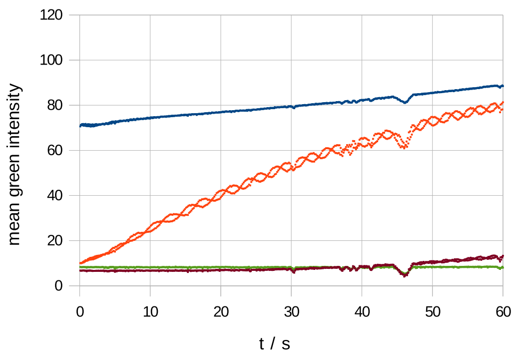


(e) Geometry A - short stroke.

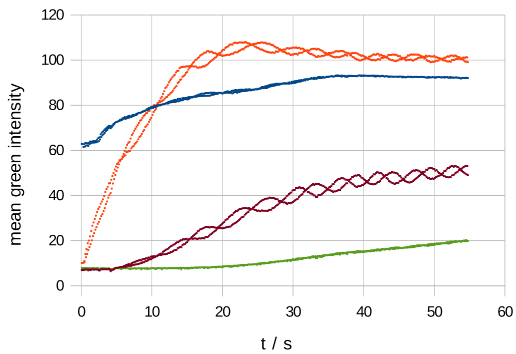


(f) Geometry C - long stroke.

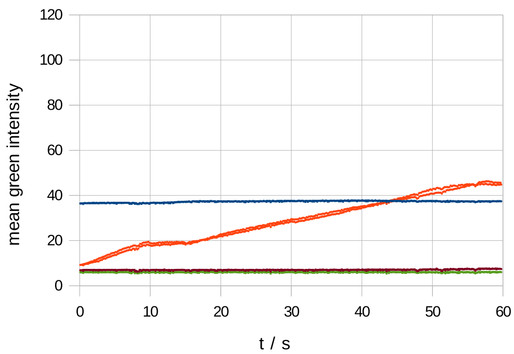
Figure 5.5: Change in dye concentration over time in geometry A-C. Blue: left chamber; red: reticulum/channels; green: left chamber.



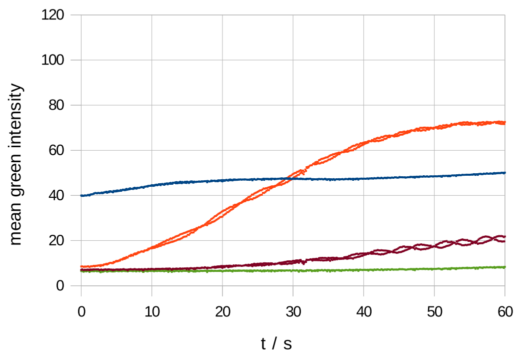
(a) Geometry D - short stroke.



(b) Geometry D - long stroke.

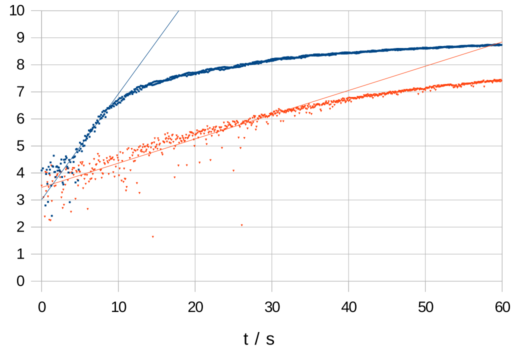


(c) Geometry E - short stroke.

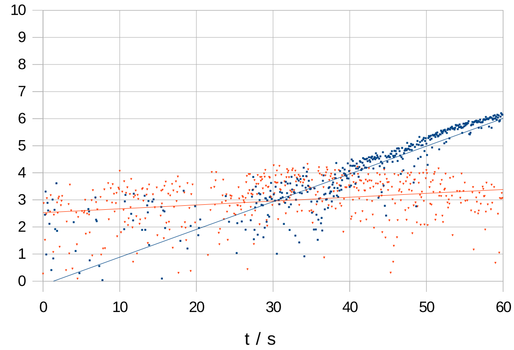


(d) Geometry E - long stroke.

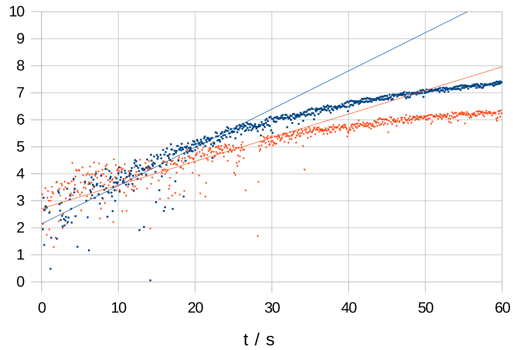
Figure 5.6: Change in dye concentration over time in geometry D-E. Blue: left chamber; red: left reticulum; purple: right reticulum; green: left chamber.



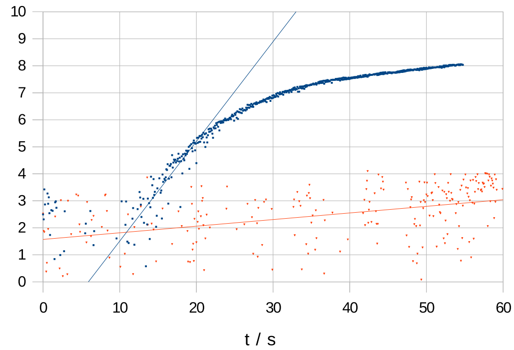
(a) Geometry A



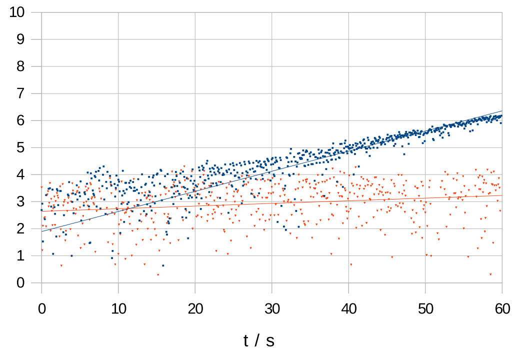
(b) Geometry B



(c) Geometry C



(d) Geometry D



(e) Geometry E

Figure 5.7: Flow rate - maximum slope of linearised right chamber concentration over time for high (blue) and low (red) amplitude. Y axis shows natural logarithm of (intensity(t) - intensity(t=0)). Straight line indicates linear regression of highest slope section. The gradient of these regressions are recorded in table 5.1.

the tested amplitudes suggest that a threshold amplitude exists where a non-linear relationship between amplitude and mass transfer takes place. At the lower oscillation amplitude the two geometries exhibit large differences in mass transfer rates, but in the higher amplitudes the difference is relatively very small. As the minimum “in-channel” amplitude is lower in geometry D than geometry A, and this effect scales linearly between low and high amplitude oscillations, the response is necessarily non-linear at some threshold value near the lower amplitude. Investigations in the previous section about frequency variations indicate that a similar threshold exists for frequency. It is not established if and how these thresholds influence each other, but it can be suggested that an increase in amplitude can compensate for a decrease in frequency and vice versa as both will increase the fluid velocity and therefore the Reynolds number. It is also likely that a frequency increase cannot always compensate for a loss of amplitude, as the amplitude affects how much “geometry irregularity” a water particle is exposed to, which is not effected by the frequency.

The lower rates of mass transfer recorded in geometry E show that the amplitude threshold of the oscillations is connected to the edge length of the network, suggesting that a larger amplitude is needed as edge lengths increase. This offers some support to the hypothesis suggested by Turner and Soar (2008) that the geometry, in this case the edge length of the network, is tuned to particular transient properties. Considering that both velocity (which determines Reynolds number) and geometric irregularities (branching, orifices, curvatures) are significant (Yellin 1966) when determining the emergence of turbulence in general terms, it appears likely that the interaction of amplitude, frequency, and edge length is determined by two properties which derive from these: velocity and distance travelled in each oscillation relative to node length. Velocity if determined by amplitude and frequency, while relative distance is determined by amplitude and edge length.

Geometry C provides an interesting data point. The geometry is branched rather than reticulated, but in practice this is a vague distinction as loops form at multiple hierarchical levels in the branching network, effectively forming reticulation. This reticulation, however, is not uniform as in geometry A and spans a range of length scales. This characteristic is shared with the network found in the egress complex, though the latter is reticulated as well. The results of this geometry are distinct because of the small difference between the small and large amplitude. These rates are both more similar to those found for small amplitude oscillations in geometry A, suggesting that the branched geometry is inferior. However, another potential hypothesis is that the prevalence of various length scales enables the network to “utilize” a larger range of amplitudes. The lower rates of transfer relative to the high amplitude oscillations in geometry A could be explained by the non-branching segment on the right side of the geometry – the “trunk” – which may block the mass transfer if it behaves similarly to geometry B. While speculative, this diversity of length scales may prove to be important if the system is designed to pick up a range of naturally occurring oscillations, such as those found in natural wind (and on which the termite mounds rely), again citing the suggestions by (Turner and Soar 2008). If the system is driven by a precise and controlled mechanically induced oscillation, it may not be an important consideration, unless such a gradient provides other benefits.

Finally, the results appear to contradict the suggestions of hypothesis G, that the mass transfer rates should be inversely proportional to the distance, or in this case that the transfer rate should be half for a doubling of the network width, as is the case in geometry D relative to geometry A. In the experiments however, the rates for geometry D were almost as high for both geometries. It is not evident what types of mechanisms would lead to these observations, and the results may stem from the increased node count of geometry D (more than twice the number of nodes).

Summary of interpretations

1. The reticulated geometry, when exposed to oscillations, exhibit significantly larger mass transfer rates than comparable non-intersecting tunnel connections.

2. Non-linear thresholds exist where significant increase of mass transfer rates take place over small changes in amplitude and/or frequency.

3. Variations of the edge (node-to-node) length appears to create a system less dependent on specific amplitudes.

4. Mass transfer rate does not correlate linearly to the overall width (depth) of the system as would be expected from Frick's Law. The results suggest that the rate may be independent of the depth, but there are indications that this may be because of the geometric variations which causes greater mixing for the wider sample.

5.5.3 Nature of flow - qualitative analysis

Hypothesis $C_{(B)}$ states that the mass transfer occurs because of the generation of turbulent flow within the reticulum. This is important because it will determine the nature of the boundary layer as is outlined in the literature review, and by extension how the flow interacts with the solids. In addition, hypothesis G is derived from this assumption, and concluding that the flow is turbulent would support this. The nature of the flow is difficult to determine from the numerical data, but visual images can give a clear picture of the flow characteristics. The visualisation studies in the previous chapter, while suggesting a turbulent mixing, are unable to show the flows within the reticulum hence the need for this visual study.

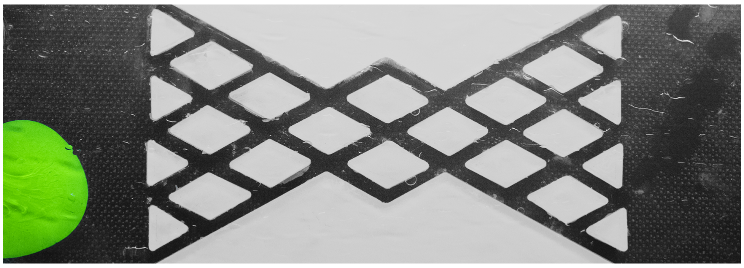
Figure 5.8 shows five sequential still images taken 0, 2, 5, 10 and 30 seconds after oscillations start. The images are taken from the experiment using geometry D and high amplitude oscillations.

From these images can be seen the emergence of significant turbulence, and that the region where mixing occurs rapidly extends away from the reticulum and engages the zone where dye is present, at a distance of 20 mm from the channel openings and beyond. Between 2 and 5 s the dye enters the reticulum, and at 10 s the dye has penetrated most of the left half of the reticulum. Significant mixing in the left chamber has occurred at 10 s. At 30 s the full left chamber contains dye and the concentration gradients are relatively smooth. The mixing zone can be concluded to extend at least 50 mm away from the channel openings.

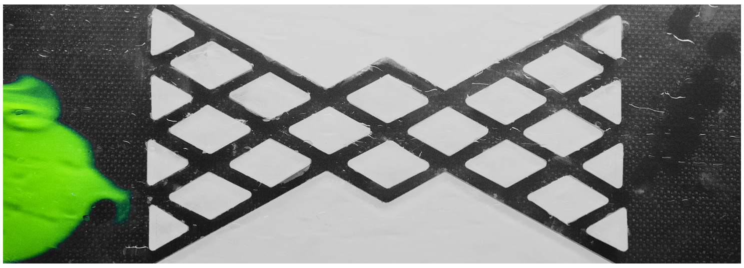
The gradients in the reticulum are very smooth, demonstrating a high level of internal mixing, more so than what is found in the chambers.

Figure 5.9 shows close-up images of the flow at t = 5 s and t = 10 s. These images demonstrate the smooth concentration gradients throughout the reticulum, and in particular demonstrate the absence of a laminar boundary layer near the solid boundaries or at flow intersections. This is particularly evident when comparing to the static flow shown in figure 5.3.

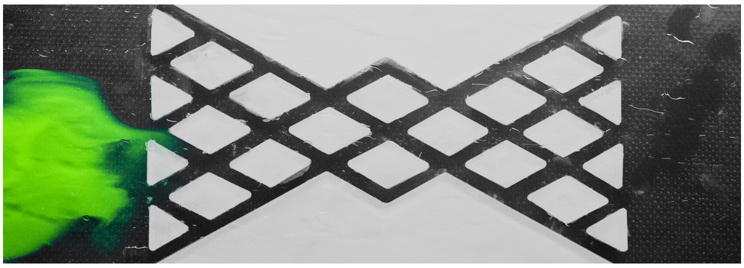
For geometry B with no reticulation, very little such turbulent flow was observed. The *Re* of both geometries is the same, and as has been stated above a Reynolds number analysis alone does not explain the formation of turbulence at these velocities. It can therefore be concluded that, in accordance to hypothesis B, the branched topology promotes the formation of turbulence at lower Reynolds numbers.



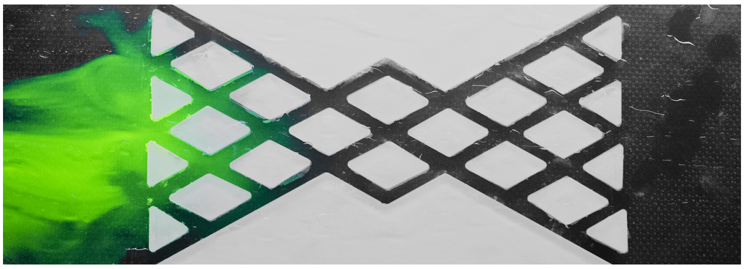
(a) t = 0 s



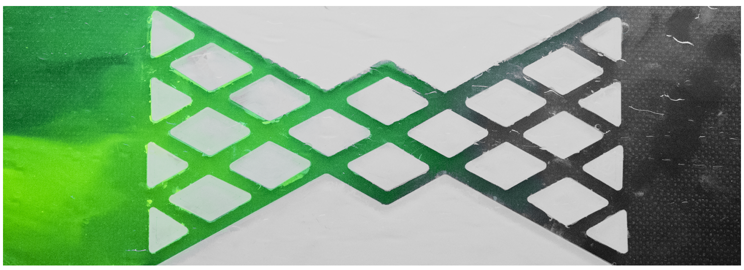
(b) t = 2 s



(c) t = 5 s



(d) t = 10 s



(e) t = 30 s

Figure 5.8: Image series showing flow patterns in geomtry D, high amplitude oscillations.

5.6 Conclusions

The experiments presented in this chapter have shown that the mixing phenomena that arise from the interaction of transient air flows and complex geometries can be induced using a 2-dimensional set-up in a different medium, in this case water. The results show that the effect appears to be easily achieved in a reticulated branching network of passages, and is not dependent on the specific topology or shape of the egress reticulum, but rather on general properties such as amount of reticulation and average edge length[4].

The scaling of frequencies following with the change of medium from air to water have been examined from the perspective of Womersley numbers, and while the prediction based on this analysis is not identical to what is found in the experiments, is is also not far off: the two systems (3-dimensional air and 2-dimensional water) exhibit significant similarity, and it appears justified to assume that the two are analogous and that behaviour learned from one can be applied to the other.

5.6.1 Influence of geometry

It has been found that the reticulated nature of the channel or passage network is critical for driving mass transfer through an oscillating airflow. The straight connections in geometry B showed very little mass transfer in spite of a larger minimum cross-sectional width than the other geometries. The branched network of geometry C demonstrated interesting properties, which may indicate that the variable node-to-node distance of this model can be driven from a wider range of amplitudes than the more uniform geometry of A. However, this conclusion is tentative as the overall rates observed in this geometry were lower than those seen in geometry A.

Increasing the node-to-node distance appears to have an detrimental effect on the rate of mass transfer for the range of frequencies and amplitudes studied in these experiments. Whether these differences would disappear at higher amplitudes in unclear. It is also possible that the mass transfer rates drop off at larger amplitudes (though this seems unlikely) or that the gain for increasing the energy input is decreased, and that the larger node-to-node distances would be more efficient at driving mass transfer in scenarios with larger total energy input.

5.6.2 Influence of oscillating flow

As seen in the previous chapter, increasing the amplitude of oscillations leads to a higher mass transfer rate. There also appears to be a threshold with a minimum amplitude required in order to convert the laminar, reversible flows of each stroke to a turbulent flow which enhances the rate of mass transfer. This threshold corresponded to a Reynolds number which was about two orders of magnitude lower than what is typically required for the emergence of turbulent flow in straight pipes. Increasing the node-no-node distance of the reticulum requires the amplitude to increase in order to achieve similar mixing rates.

Similarly, a threshold exists for a minimum frequency at which the mass transfer rates increase significantly. No upper bound was found for a maximum frequency, as was observed in the 3-dimensional experiments. However, the experiment apparatus limited the investigations to

[4]Although the specific and general shape and topology of the egress complex is likely to hold considerable functionality beyond those which can be captured by the simpler models used here.

approximately 6.5 Hz, which was close to the minimum threshold and if an upper threshold exists this would likely not have been discovered in the experiments performed.

Testing the effects of the oscillations on mass transfer rates is relatively straight forward, and can easily be performed for a specific geometry after this has been manufactured. Knowing the exact behaviour and interaction between a specific geometry and the oscillations is therefore not critical, as the oscillations can be adapted to the specific use scenario after the fabrication and design of this product.

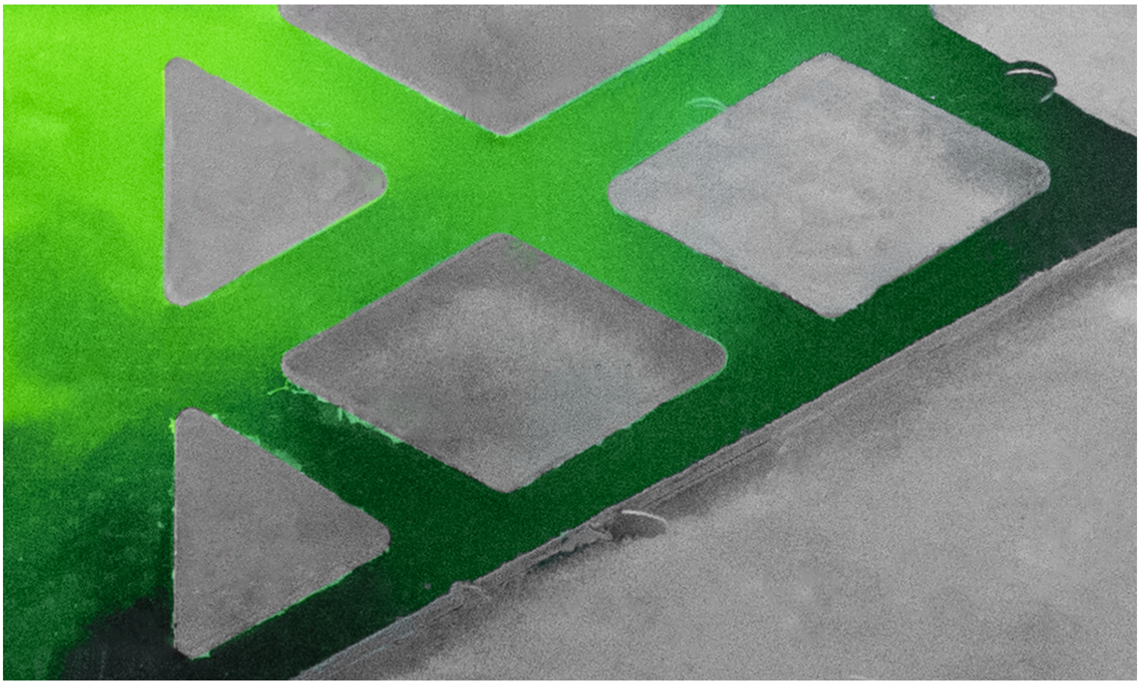
A possible hypothesis for the relationship between flow properties and network geometry was suggested where the emergence of turbulence is determined by an combination of the velocity (or acceleration) of the flow and the ratio of displacement amplitude relative to edge length. The velocity is the product of frequency and amplitude, and from these a testable mathematical relationship can be determined.

5.6.3 Nature of flow

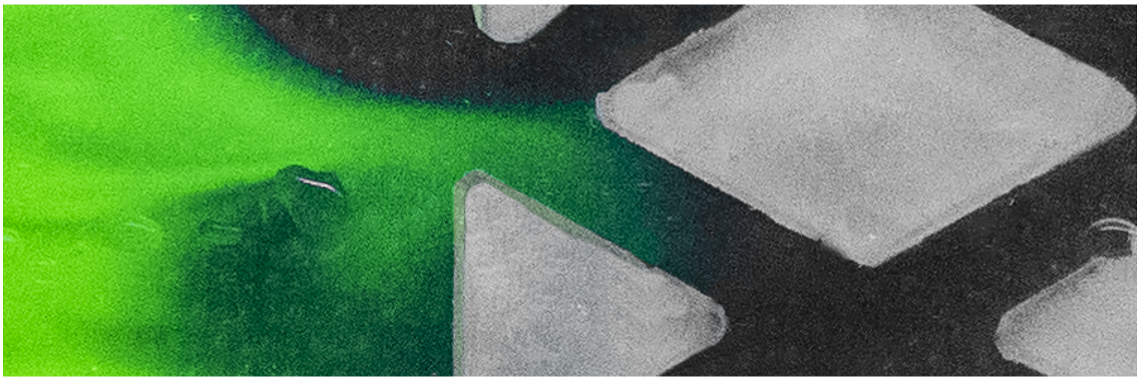
Observations of the nature of the flow have shown that the reversible (laminar), back-and-forth flow driven by the piston transforms as thresholds in frequency and amplitude are crossed, at which point the flow becomes turbulent and non-reversible. This turbulent flow leads to significant mixing of the fluid volumes in and near the network of reticulated channels. The turbulent zone extends at least 50 mm away from the channel openings into the left and right chambers.

The results regarding hypothesis G, that the mass transfer rates scale inversely to distance in accordance to Frick's Law, were inconclusive. The theoretical basis for this assumption were confirmed by the observation of turbulent mixing, but the mass transfer rates for geometry D realtive to geometry A were higher than what would be expected from Frick's Law. It was suggested that this may be because of effects of the increased node count which compensate for the larger distance.

Relative to a laminar, static flow the turbulent flow observed is distinguished by the lack of a laminar boundary layer. This can be observed in figures 5.8, particularly in relation to figures 5.3. A consequence of this flow characteristic is that the fluid is brought in constant contact with the wall solids, allowing for interchange between the fluid and solids to a greater extent than would be the case form a static flow (Vogel 1996, pp. 161–162, 312). This applies equally to any particles being carried by the fluid and brought along the flow.



(a) t = 12 s



(b) t = 5 s

Figure 5.9: Images show close up views of flows at 12 s and 5 s (geometry D, high amplitude). Note the smooth cross sectional profile of dye concentration, showing the absence of boundary layer (compare to figure 5.3.) (Images have been digitally cleaned to enhance legibility.)

Chapter 6

Mass Transfer Induced by External Turbulent Flows

Even though developments in analysing and simulating the interior environment have revealed the remarkable variability and transiency of that environment, we stubbornly cling to the belief that the envelope supersedes all – acting as a barrier to the exterior, container of the interior and determinant of all extant physical phenomena. Essentially, we privilege that which we know, that which we see, that which matches our image of a permanent and static architecture.

– Michelle Addington[1]

6.1 Introduction

The results described in the previous chapters have shown that the specific geometry of the egress complex found in the *M. michaelseni* termite mounds interact with an oscillating (0-net flow) airflow to drive significant mass transfer. The particular interest in this phenomenon from an architectural perspective lies in the potential application of these mechanisms to control and manipulate internal climates, whether through integration in building envelopes or other structures.

[1] (Addington 2009, p.16)

The research presented in this chapter investigates means to drive and utilize those mechanisms, and how they may behave functionally from a construction engineering perspective. This is divided into two main sections, the first relating the the potential for utilizing external wind flows as a driver for the mass transfer. This can potentially enable an entirely passive system which can perform its function without any externally supplied energy and without active control. It also provides an opportunity to test whether the simple interaction of the EC geometry and naturally occurring winds is the main mass transfer mechanism in the termite mound. These investigations can be summarised by testing three hypotheses:

H The turbulence observed to arise from induced oscillations can also be generated by exposing the outer panel surface to transient air flows such as those caused by wind.

I The wind-induced mass transfer depends on the same geometric parameters as the oscillation induced flow.

J As in the oscillation induced scenario, the mass transfer rates depend on mixing, and are proportional to *Frick's Law* of diffusion.

The first two can on the one hand determine if the reticulated geometry can be exploited in passive systems, which rely on external wind as energy source. If both the first (H) and the second (I) are true then it also means that the mechanisms described in the previous chapter are generated by wind, and are likely to take place and be an energy source in the mound. If (I) is false however, this indicates that either the oscillation induced mass transfer does not take place in the termite mound, or there are more complex phenomena which likely involve the rest of the mound geometry. This would not preclude the potential use of the reticulated geometry as a mass transfer mechanism in buildings however. The third hypothesis relates to the scaling of the mass transfer relative to the wall thickness, and enables a comparison of the naturally induced and the oscillation induced mass transfer, as well as providing critical data for the potential dimensioning of engineered ventilation systems.

The second section investigates the associated or secondary flows of mass and energy which take place during the transient mass transfer processes: this includes investigations of the heat flows coinciding with the mass transfer, and flows between the fluid in the EC panels and the panel itself. These are expressed as two testable hypotheses:

K If the interior and exterior air volumes are of different temperature, the heat transfer will be the same as the difference in sensible heat of the equivalent flow.

L The turbulent nature of the flows means there is a significant exchange of heat and water between the air in the channels and the panel material.

The first is important from an energy conservation perspective. As the flows are 0-net bulk flows it is not fully evident that this should be the case, as there may be small scale counter flow mechanisms taking place. In addition, there has been suggestions in literature that the flows within the mounds are constructed to me discriminatory, i.e. promoting one type of transfer but discouraging others (Turner and Soar 2008). However, these suggestions mostly relate to spatial variability and the termites' ability to actively transport water between different regions. The latter (L) hypothesis is perhaps the most interesting, and is founded on the turbulent nature of the flow which should facilitate a large exchange between the panel materials and the flow across the panel.

6.2 Wind driven transient mass transfer

One possible way to utilize the described mechanisms lies in their direct application, i.e. through mechanically induced oscillations. However, an alternative and potentially attractive solution would be if the transient state arises independently when the geometry of the EC is exposed to wind events found naturally around potential buildings. Turner (2001) suggests that at least a component of the mound respiratory gas exchange is driven by forced convection arising from turbulent air movements outside the mound. It is unclear however to what extent the egress geometry of the mound is involved in harnessing this energy, and what aspects of the mound geometry and physiology are critical for the mass transfer to take place. Therefore, the following experiments have been undertaken in order to clarify how the egress complex responds to such eddies of turbulent wind, and whether this allows for a potential engineering application.

Three different hypotheses are tested here. The first is to determine whether these panels, when exposed to external turbulence exhibit similar mass transfer rates to those previously crated through oscillations of the air. The second hypothesis is concerned with establishing if the panel parameters such as reticulation have the same relationship to the mass transfer rates as has been demonstrated in the previous experiments. The reason this is important is that it may be, as Turner and Soar (2008) speculate, that the transient wind causes ’sloshing’ or oscillation within the channels which lead to internal turbulence through the same mechanisms as have been documented in the previous chapters. But it is equally possible that the external turbulence simply penetrates the tunnels and causes mixing themselves. In this case, it seems likely that all panels will exhibit similar levels of mass transfer with no correlation to reticulation.

The final hypothesis concerns the effect of wall thickness on the mass transfer rates. As was proposed in the previous chapter, a pure mixing phenomena should dictate that the mass transfer, or equivalent flow, is proportional to the inverse of the thickness. If the mass transfer is caused by penetrating external turbulence this is likely to lose energy and intensity deeper into the wall, which would lead to a lower mass transfer rate than predicted by Frick’s law. On the other hand, a cross flow would not exhibit this decay with increasing thickness (but would lose energy to wall friction in a similar manner).

6.2.1 Experiment set-up

As previously, the egress complex was mounted in a wooden frame which was set on a test chamber made from 50 mm thick extruded polystyrene with an internal coating of polyvinyl acetate in order to minimise gas permeability. All joints were sealed with gaskets. The volume of the test chamber was 11.7 litres. The set up is illustrated in figure 6.1.

The test rig was placed in a room with low but not negligible air movement. A fan was placed at approximately 1,500 mm distance from the outside membrane surface (position A in figure 6.2) and a potted plant placed in between the fan and test chamber (position B) in order to maximise turbulent flows and reduce direct, laminar flows. The fan was 150 mm diameter with a max effect of 15 W, with a low and high effect setting.

In order to track the mass transfer across the egress complex in varying scenarios a COZIR Wide Range CO_2 sensor was placed inside the test chamber, at position A in figure 6.1. Air with an elevated level of CO_2 was introduced into the chamber, and the decay rate was recorded. Through linear regression of the CO_2 concentrations an air change rate was calculated according

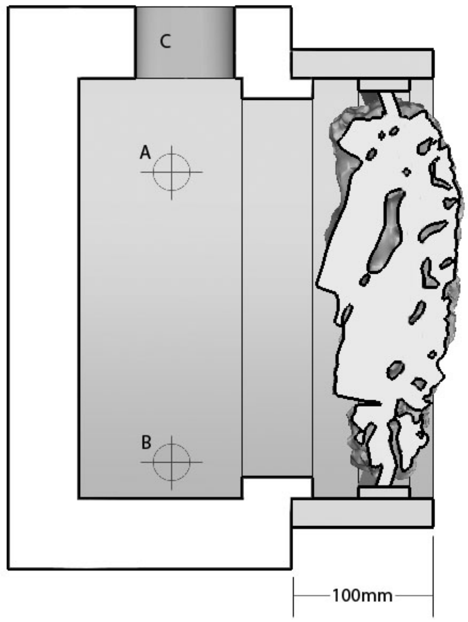


Figure 6.1: Section through panel mounted in test chamber. A indicates sensor placement, B indicates placement of heat source when used, C a removable insulated lid for access. White indicates extruded polystyrene, dark grey wood, and light grey is the EC membrane, made from sintered nylon.

to Sherman (1990), which can be converted to an equivalent continuous flow using the volume of the test chamber.

Natural wind exposure

While the flow from the fan was set up to be highly turbulent, it also remained without great variations, and any systematic differences from actual wind exposure are difficult to qualify without making a very large number of experiment variations. This means the replicability between experiments is maximised, but carries with it other issues with regards to the relevance or the experimental data in "real" situations. To address this another set of experiments was performed where the test chamber and panels were placed outside in exposure to wind and the CO_2 decay rates were similarly tracked.

Time	Temperature	Wind	Rain	Humidity	Pressure
Fri 10.00	5 °C	E 5 (10) m/s	0.0 mm/h	66%	1018 hPa
Fri 11.00	6 °C	E 6 (11) m/s	0.0 mm/h	57%	1019 hPa
Fri 12.00	6 °C	E 6 (11) m/s	0.0 mm/h	52%	1019 hPa
Fri 13.00	7 °C	E 6 (12) m/s	0.0 mm/h	50%	1019 hPa
Fri 14.00	7 °C	E 7 (12) m/s	0.0 mm/h	48%	1019 hPa
Fri 15.00	7 °C	E 7 (12) m/s	0.0 mm/h	47%	1019 hPa

Table 6.1: Weather in Teckomatorp, Sweden 04 April 2014.

The experiments were carried out over a 3 hour period between 11.00 and 14.00 on the 4th of April 2014 in Teckomatorp, Sweden. The weather conditions as reported by SMHI are shown in table 6.1, and the reported wind speed is slightly higher than average wind for the area. In order to minimise differences between the experiment runs due to changing wind conditions, the panels

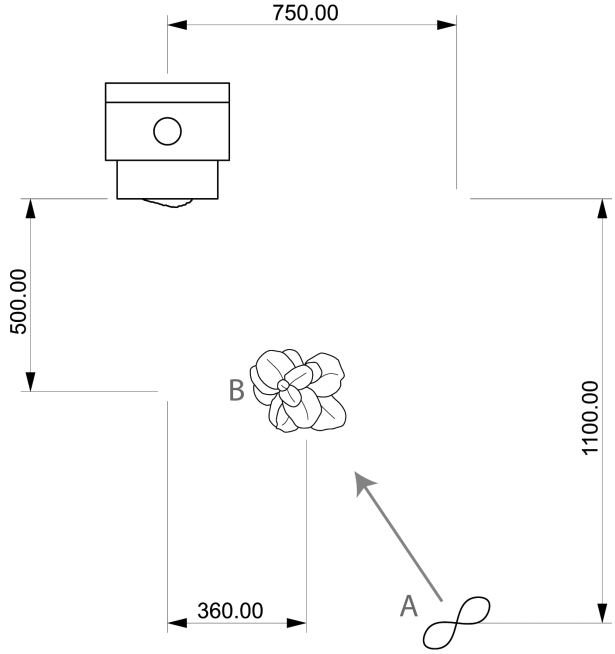


Figure 6.2: Plan showing placement of fan relative to test chamber.

were tested interchangeably, with the EC scan tested twice, then variant A twice, then the EC scan again and so on.

6.2.2 Experiments conducted

The described set-up was used to investigate a number of panels and flow conditions, with the intent to test first what mass transfer can be induced in these conditions, and secondly to determine if the geometric dependence is the same as in the previous tests in chapter 4. The panels tested were the same as those described in 4.4.2, with the addition of one additional panel called "variant D". This panel was modelled on Variant C, but with a random reticulation (thus a slightly different topology than the EC), and with a greater depth, 150 mm instead of 50 mm as was the case with all other panels including the EC. This panel was added in order to test the relationship between mass transfer rates and and panel thickness, and to provide data that can help dimension a potential architectural implementation with regards to wall thickness.

In order to test a range of flow conditions which may approximate the exposure of the termite mound to winds, the flow was varied by alterations of the fan placement and the placement of an obstacle in the path between the fan and the panel. In the final experiment, the panels were placed in outdoor conditions where they were exposed to natural wind. This is the most realistic scenario, but also with the highest level of variability. This was addressed by conducting a large number of experiments in measured and similar conditions.

The experiments conducted are shown in table 6.2 which reference figure 6.2 for relative positions. The experiments are named according to the following system: ($P_{\#}$)-(Letter):(#). ($P_{\#}$) indicates which panel was tested, the following letter indicates the flow conditions according to the table, and the final number is the differentiator for a sequence of identical experiments.

Experiment runs Z provide the baseline with no air movements though in reality some air movements were and will always be present and this value does not represent a pure diffusion. However, any convection was significantly lower than what was induced by the fan when this was

Fan	Panel				
	EC scan	Variant A	Variant B	Variant C	Variant D
No fan	P_{EC}-Z	P_A-Z	P_B-Z	P_C-Z	P_D-Z
No fan, perforations in panel covered	P_{EC}-X	-	-	-	-
Fan low, position A. Plant at position B	P_{EC}-A	P_A-A	P_B-A	P_C-A	P_D-A
Fan high, position A. Plant at position B	P_{EC}-B	-	-	-	-
Fan low, position A	P_{EC}-C	-	-	-	-
Fan low, position B	P_{EC}-D	P_A-C	-	-	-
Panel outside, exposed to ambient wind	P_{EC}-Y	P_A-Y	-	-	-

Table 6.2: List of experiments - wind driven mass transfer.

used. For experiment X the perforations in the EC were covered up with a layer of aluminium foil and intended to provide an estimate of the losses in the chamber itself. A-C provide different turbulent flows at the EC opening, with B intended to create greater turbulence than A and C intended to create a stronger flow. In experiment D the fan is positioned close enough to the EC to create a clear pressure differential between the lower half of the EC surface and the upper half, thus likely inducing a circular, steady flow across the EC. Experiment Y exposed the panels to outside wind conditions as described in the previous section.

6.2.3 Results

The results recorded for panel EC, which is the scanned and printed egress complex, are shown in figure 6.3 in the form of the natural logarithm and linear regression of all the experiment runs P_{EC}:Z to P_{EC}:D (P_{EC}:Y, the experiment conducted outside in natural wind exposure is shown further down). The calculated mass transfer is shown in table 6.3, together with the standard deviation of the experiments.

P_{EC}-X represents the mass transfer though other pathways than the perforations in the membrane, as the outer surface of the membrane was sealed with aluminium foil. Potential pathways include leakiness of the chamber, and absorption of CO_2 in the walls of the test chamber or the membrane itself.

The baseline (P_{EC}-Z) should indicate the normal convection/diffusion in still air. The mass transfer in this scenario is approximately 0.5 airchanges per 1000 seconds, out of which 40% can be attributed to losses through other means than the perforations, as measured in P_{EC}-X.

Measurement	Experiment					
	P_{EC}-Z	P_{EC}-X	P_{EC}-A	P_{EC}-B	P_{EC}-C	P_{EC}-D
Airchanges / 1,000s:	0.506	0.213	7.48	5.94	7.77	23.2
Equivalent flow (l/s):	5.92×10^{-3}	2.49×10^{-3}	87.5×10^{-3}	69.5×10^{-3}	90.9×10^{-3}	271×10^{-3}
Standard deviation (1σ):	8.0%	11%	3.3%	24%	19%	8.3%

Table 6.3: Airchange rates for panel EC (egress complex SLS print). 2nd row contains equivalent flow based on a chamber volume of 11.7l, 3rd row contains the standard deviation of the average airchange rate for multiple executions of each experiment.

With the introduction of a fan which drives turbulent air movements at the outer face of the egress complex, the mass transfer rate increases significantly, to about 7.5 airchanges per 1000 seconds (P_{EC}-A). Subtracting the leakiness losses (P_{EC}-X), this represents a 24-fold increase of mass transfer over the baseline, P_{EC}-Z.

The small alterations of the set up, P_{EC}-B and C, where the fan power was increased and the plant was removed respectively show small changes from the mass transfer in P_{EC}-A, which are likely within the margin of error of the experiment. However, as the fan was moved to a position closer to the outer surface of the EC, the mass transfer rate increased to 23 airchanges per 1000 seconds, three times that where the fan was placed further from the panel. At this distance the pressure from the fan is unevenly distributed across the face of the panel, presumably leading to a continuous flow across the egress complex with a net flow in through the channels closest to the air stream of the fan and a net flow out through those furthest away.

Geometric variations

The graphs in figure 6.4 show the linearised CO_2 decay for all 4 panels in static air, with the corresponding table 6.4 showing average airchanges per time and equivalent airflow, plus the standard deviation for the average. Figure 6.5 graphs show the linearised CO_2 decay for all 4 panels in turbulent air, with the corresponding table 6.5. Finally graphs in figure 6.6 show the EC scan panel and variant A panel in continuous flow (where the fan is placed close enough to the panel to create a static pressure differential across the upper and lower portions of the panel surface). The corresponding data is shown in table 6.6.

Measurement	Panel			
	EC scan (P_{EC}-Z)	Variant A (P_AZ)	Variant B (P_B-Z)	Variant C (WP_CZ)
Airchanges / 1,000s:	0.506	0.486	0.557	0.459
Equivalent flow (l/s):	5.92×10^{-3}	5.69×10^{-3}	6.52×10^{-3}	5.37×10^{-3}
Standard deviation (1σ):	8.0%	4.1%	10%	1.9%

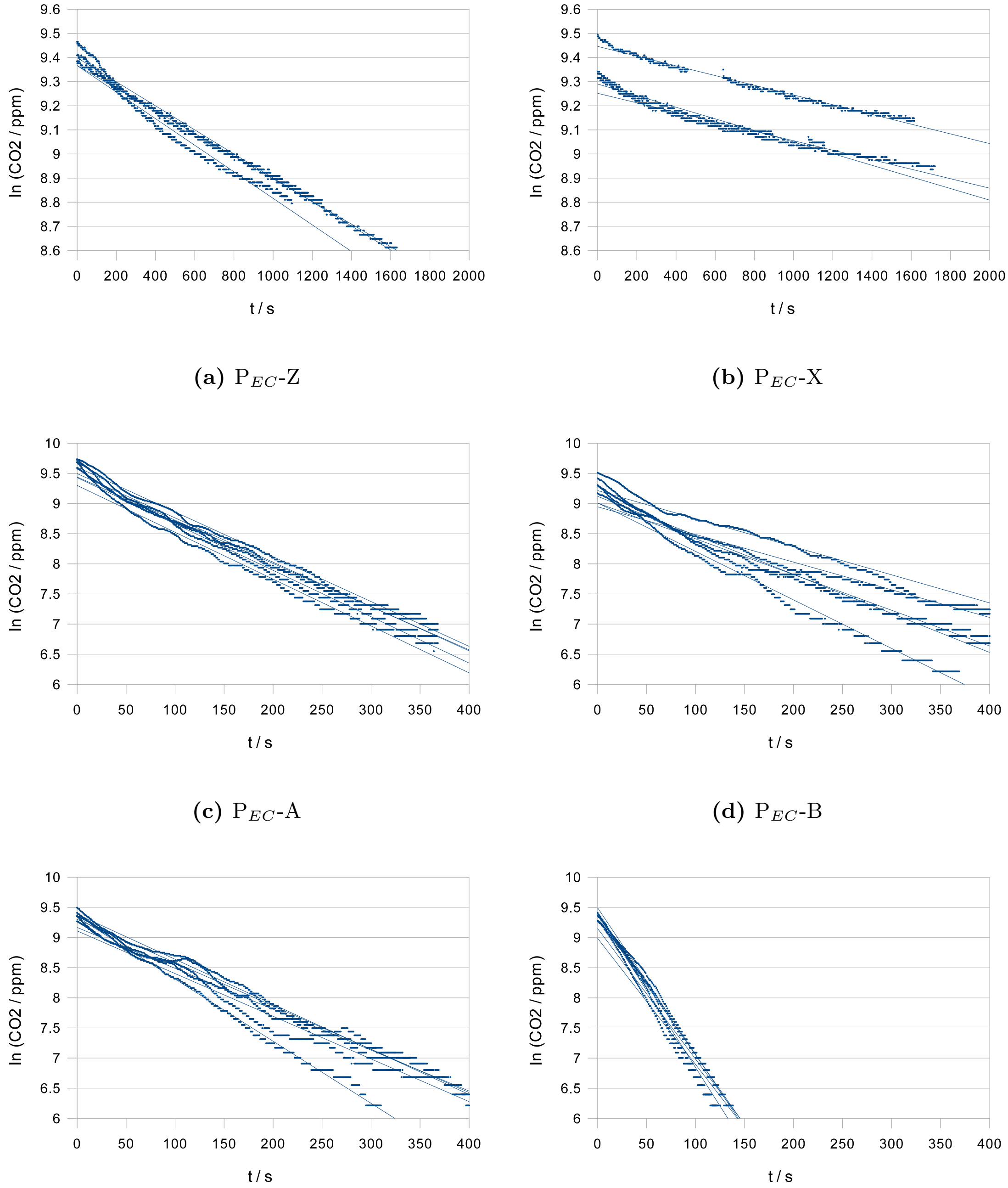
Table 6.4: Airchange rates for different panels in static air (P_{EC-C}-Z). 2nd row contains equivalent flow based on a chamber volume of 11.7l, 3rd row contains the standard deviation of the average airchange rate for multiple executions of each experiment.

Measurement	Panel			
	EC scan (P_{EC}-A)	Variant A (P_A-A)	Variant B (P_B-A)	Variant C (P_C-A)
Airchanges / 1,000s:	7.48	6.35	5.21	5.32
Equivalent flow (l/s):	8.75×10^{-2}	7.43×10^{-2}	6.10×10^{-2}	6.22×10^{-2}
Standard deviation (1σ):	3.3%	5.9%	4.8%	7.9%

Table 6.5: Airchange rates for different panels in turbulent air (P_{EC-C}-A). 2nd row contains equivalent flow based on a chamber volume of 11.7l, 3rd row contains the standard deviation of the average airchange rate for multiple executions of each experiment.

Measurement	Panel	
	EC scan (P_{EC}-D)	Variant A (P_A-D)
Airchanges / 1,000s:	23.2	21.2
Equivalent flow (l/s):	2.71×10^{-1}	2.48×10^{-1}
Standard deviation (1σ):	8.3%	6.5%

Table 6.6: Airchange rates for different panels in continuous flow (P_{EC-A}-D). 2nd row contains equivalent flow based on a chamber volume of 11.7l, 3rd row contains the standard deviation of the average airchange rate for multiple executions of each experiment.



(a) P_{EC}-Z

(b) P_{EC}-X

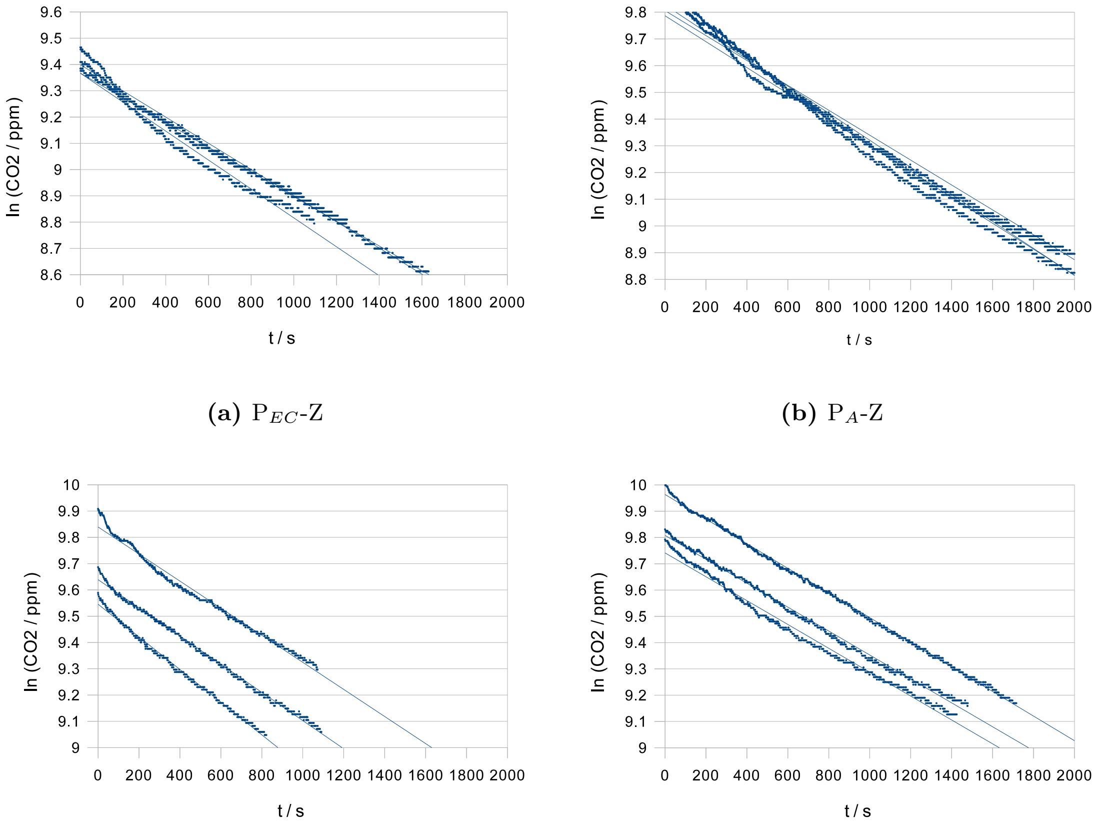
(c) P_{EC}-A

(d) P_{EC}-B

(e) P_{EC}-C

(f) WP_{EC}-D

Figure 6.3: Natural logaritm of CO_2 concentration tracking decay rate for panel B (EC SLS print) in varying conditions.



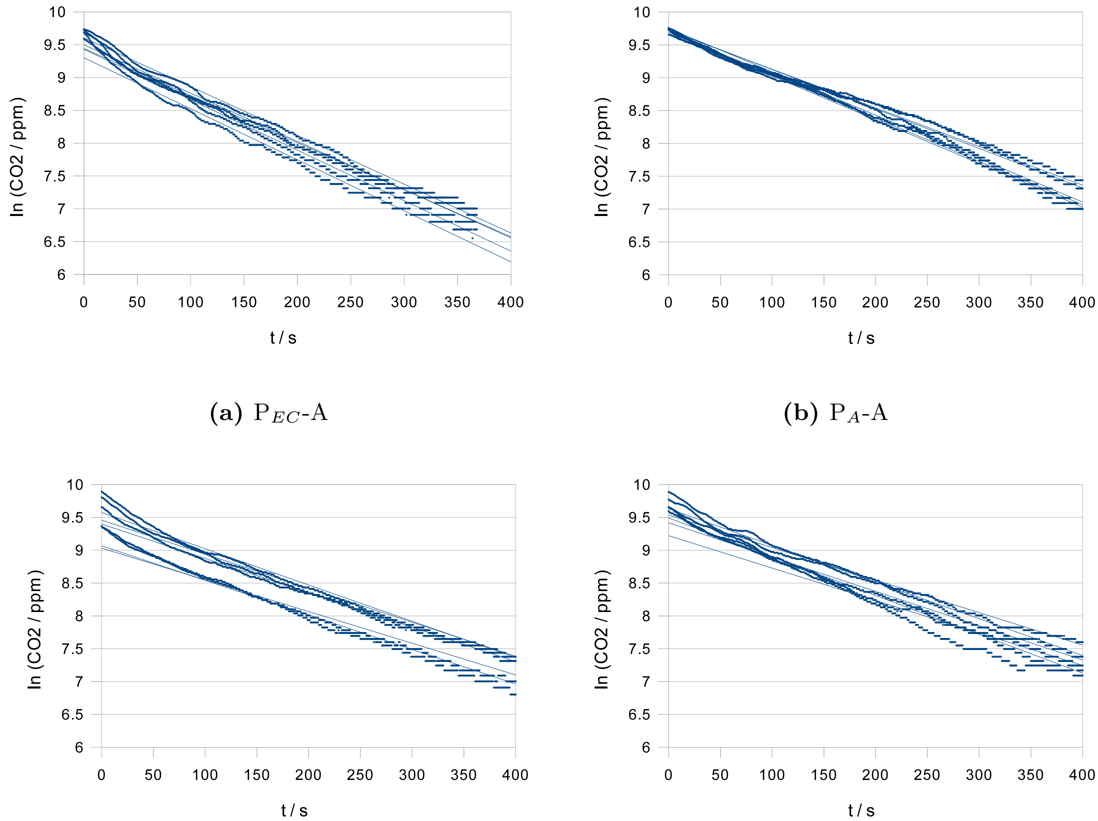
(a) P_{EC}-Z

(b) P_A-Z

(c) P_B-Z

(d) P_C-Z

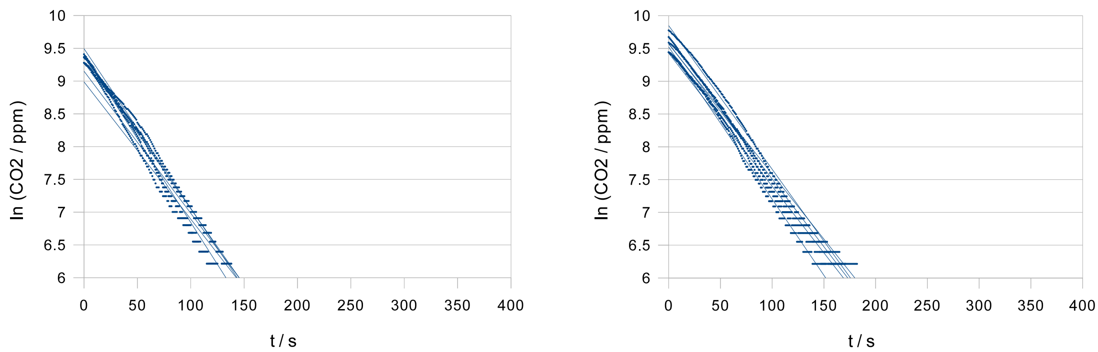
Figure 6.4: Panel comparison. Natural logarithm of CO_2 concentration tracking decay rate in static air for panels P_{EC-C}.



(a) P_{EC}-A **(b)** P_A-A

(c) P_B-A **(d)** P_C-A

Figure 6.5: Panel comparison. Natural logaritm of CO_2 concentration tracking decay rate in turbulent air for panels P_{EC-C}.



(a) P_{EC}-D **(b)** P_AD

Figure 6.6: Panel comparison. Natural logaritm of CO_2 concentration tracking decay rate in continuous flow for panels P_{EC} and P_A.

Measurement	Panel	
	EC scan (P_{EC}-Y)	Variant A (P_A-Y)
Airchanges / 1,000s:	5.12	6.81
Equivalent flow (l/s):	5.99×10^{-2}	7.97×10^{-2}
Standard deviation (1σ):	17%	13%

Table 6.7: Airchange rates for different panels in wind-induced convection flow (P_{EC-A}-Y). 2nd row contains equivalent flow based on a chamber volume of 11.7 l, 3rd row contains the standard deviation of the average airchange rate for multiple executions of each experiment.

Wall thickness variation

A panel with an artificially created reticulated channel geometry with a greater thickness (approximtely 150 mm) was made and tested. The mass transfer rate for this panel was measured to 3.13 airchanges per 1000 s at low fan settings. This is approximately 42% of the flow found for panel B (7.48 ach/1000 s), which is the printed egress complex scan. The mass transfer rate at no induced wind motion was 0.26 ach/1000 s, compared to 0.51 for panel B.

Natural wind

Figure 6.7 shows the linearised CO_2 decay in the experiment runs conducted outside in natural wind conditions (P_{EC-A}-Y). Blue indicates the EC scan panel (P_{EC}), and red the Variant A panel (P_A). The slope overall is slightly steeper for the Variant A runs, as is confirmed in table 6.7; the average equivalent flow is approximately 0.08 l/s for variant A and 0.06 l/s for the EC scan. This result differs slightly from the findings when using the fan in controlled conditions, where the mass transfer was larger for the EC scan panel than the variant A panel.

6.2.4 Interpretation of results

From these results can be concluded two significant findings: That a mass transfer of a similar magnitude to that observed in the oscillation induced transfer can be achieved across the panels by exposing the outer surface to turbulent wind, and that the rate of mass transfer in this case appears to be more of less independent from the specific topology of the tunnel network. This indicates that the reticulated geometry, which was found to be associated with higher mass transfer rates in the previous two chapters, is involved in the translation of oscillations into turbulent flow, but not in wind turbulence into oscillations. That is, the hypothesis that wind energy, via oscillations or 'sloshing' caused by the EC geometry is converted to internal turbulence appears to be unfounded. This may indicate that the mechanisms described in chapter 4 and 5 are not a significant part of the mound mass transfer, or it may indicate that the larger mound geometry is necessary for this conversion to work (for example resonance effects in the surface conduits), and that the EC in isolation cannot perform this work.

The rates of mass transfer appear to be relatively robust with regards to the nature of the turbulent flow applied, and these results are also consistent when the fan-induced flows are replaced with natural winds.

A secondary finding is that the thickness of the wall limits the penetration of the turbulent flow and reduces the mass transfer rates. This is different from the oscillation induced flow, which was shown in chapter 5 to be independent of the reticulum depth, though there are some reservations to this finding in the previous chapter. This is consistent with a hypothesis that the oscillations generate turbulence within the full length of the reticulum, whereas the turbulence in this case is external and loses energy and intensity as it penetrates into the channels. This reduction was found to be less than a proportional reduction relative to the wall thickness, as a 200% increase in thickness (50 to 150 mm) resulted in a 58% reduction of mass transfer.

Because of the multiple variables involved, it is difficult to draw full conclusions on the nature of the flow and how it responds to wall thickness, but the experiment data provides valuable input for design implementation, and suggests that a fully wind powered system is more susceptible to loss of mass transfer due to increased panel thickness than is an oscillation assisted system.

6.3 Associated flows of matter and energy

In the previous section was explored how the tested panels interact with external turbulent flows, and how this flow leads to an exchange of gasses between the two sides of the panel. This section investigates the associated, or secondary, flows of this mass transfer. These include the flows of heat within the flowing or turbulent air (which typically behave the same as the air which carries them), and the flows of heat, water and particles between the air and any solid surfaces it passes over, in this case the panel itself. These associated flows are of critical importance in engineering applications, mostly though their importance in buffering/storage/capture mechanisms. In this section is reported a series of experiments which investigate the nature of these associated flows.

6.3.1 Experiments conducted

Four experiments were conducted, all of which use the same basic set-up as described in section 6.2. The first is designed to correlate the changes in temperature and CO_2 concentration within the ventilated chamber, where the temperature is expected to be 'sticky' relative to CO_2 concentration due to the heat exchange between the solid surfaces which act as buffers. The second test whether the heat loss associated with the ventilation is the same as would be expected from a steady flow ventilation. The third and fourth experiments explore how the solid panel interacts with the fluids in the channels, and the exchange of water and heat between them, based on the hypothesis that the turbulent nature of the flows should enable a rapid homogenisation of the temperature, alternatively moisture level, of the panel surfaces and the air in the channels. All of these experiments were conducted using the Egress Complex (EC) scan panel (P_{EC}), and are listed in table 6.8.

Experiment	Description
6.3:1	Tracking internal temperature change relative to CO_2 concentration.
6.3:2	Measurement of internal steady state temperature with internal heat source.
6.3:3	Tracking internal temperature change - flow across cooled panel
6.3:4	Tracking internal temperature change - flow across wet panel

Table 6.8: List of experiments - associated flows.

Heat loss during fan-induced convection

In this first experiment the set-up was identical to the experiments described in figure 6.2 and 6.1, but with the sensor also tracking temperature. The ambient temperature was 2 °C, the test chamber was slightly warmer than ambient (approx. 4 °C), and the gas that was introduced to the chamber was equalised to the same temperature as the chamber before the experiment started.

The experiment was run with the fan on for 22 minutes, after which the fan was turned off and after a brief pause the sensors were moved to the outside of the insulated box where they were left in ambient conditions until the sensor recording stabilised.

Steady state temperature with internal heat source

The previous experiment (6.3:1) does not take into account the stored sensible heat of the panel and chamber, and as the volumes of mass transfer are small in relation to the panel mass, another experiment was needed to isolate the heat loss to the environment. This was done by introducing an internal heat source to the chamber and allowing the system to settle into a steady state temperature while the fan was turned on. The panels and test chamber were placed in identical positions as in the previous experiments. A thermocouple sensor was placed in the test chamber (position A in figure 6.1) together with a 15W heat source in the form of a filament bulb (position B in figure 6.1). The temperature was then tracked under several hours as it stabilised and approximated the steady state temperature, as is show in figure 6.8. This experiment was repeated with panels 1 (EC scan) and 2 (Variant A), with fan positions as those used in section 6.2.

From these steady state temperatures was calculated the effective heat loss from the system through the transient flow.

Heat transfer between panel and ventilated air

This experiment was intended to investigate the transfer of hear between the panel material and and the ventilated air that passes through it. The panels (EC scan) and variant A (straight perforations) were placed in a cold compartment over night until they had stabilized in a uniform temperature at -18 °C. The panels were then attached to the insulated chamber (which was at ambient temperature) and placed in the standard test setting as shown in figure 6.2. The fan, placed in position A was turned on at 'low' setting. Ambient temperature in the room was 14.6 °C.

Evaporation and cooling of ventilation air

The two panels (B and C) were soaked in water, which was readily absorbed by the porous, sintered nylon materials of the prints. They were mounted to the chamber, and placed in an arrangement shown in figure 6.2. The whole set-up was placed in non-windy conditions with an ambient temperature of 25.7 °C, and ambient humidity around 46% for panel B and 50% for panel C. This corresponds to an approximate wet bulb temperature of 18.0 °C for panel B and 18.5 °C for panel C (see figure 3.5). The fan was used to create a transient flow condition, and the relative humidity and temperature of the internal test chamber was recorded over a time of 2,000 s.

6.3.2 Results

Heat loss during fan-induced convection

The outcome of experiment 6.3:1 is described in figure 6.9, and shows the temperature remaining constant at around 4 °C over 1,300 seconds as the CO_2 rapidly drops to ambient. As the sensor is moved out of the test chamber into ambient temperatures, temperature readout immediately starts dropping towards ambient showing that the sensor response time is sufficient to record changes in temperature at this time scale.

	Fan position and speed						
Experiment	Ambient	X	Z	A	B	C	D
ZA2	5.7 °C		38 °C	33.5 °C			
ZA3	6.1 °C	42 °C	39 °C	35 °C			
ZA4	5.6 °C	41 °C	38.5 °C	36 °C	35.5 °C	33 °C	26 °C
ΔT average	-	36 °C	33 °C	29 °C	30 °C	27 °C	20 °C

Table 6.9: Steady state temperatures for EC scan panel. X: No fan, perforations in panel covered. Z: No fan. A: Fan low, position A; Plant at position B. B: Fan high, position A; Plant at position B. C: Fan low, position A. D: Fan low, position B.

	Fan position and speed						
Experiment	Ambient	X	Z	A	B	C	D
ZB1	6.5 °C	41 °C	40 °C	37 °C			
ZB2	6 °C		40 °C	36 °C			24 °C
ΔT average	-	35 °C	34 °C	30 °C			18 °C

Table 6.10: Steady state temperatures for Variant A panel. X: No fan, perforations in panel covered. Z: No fan. A: Fan low, position A; Plant at position B. B: Fan high, position A; Plant at position B. C: Fan low, position A. D: Fan low, position B.

Steady state temperature with internal heat source

The steady state temperatures recorded are shown in table 6.9 and 6.10.

Based on these temperatures, it is possible to calculate the heat lost from the system through the ventilated air. When the temperature in the test chamber is constant the energy balance of the system is as follows:

$$Q_{in} = Q_{out} \tag{6.1}$$

The influx of energy is equal to the effect of the bulb, i.e. 15J/s. The outflux of energy is composed of two components (assuming radiation is negligible): the first is conductive heat transfer (Q_c)which is mostly independent of air movement and thus constant, and the second is convective heat transfer which is dependent on the airflow across the membrane (Q_t) and varies with the ventilation.

$$15J/s = \frac{\Delta Q_c}{\Delta t} + \frac{\Delta Q_t}{\Delta t} \tag{6.2}$$

The conductive heat transfer is defined as:

$$Q_c = a \cdot \Delta T \cdot s \tag{6.3}$$

Where a is the thermal conductivity factor for this specific box which is constant. Combining (2) and (3) while assuming that convective heat is 0 gives:

$$15J/s = a \cdot \Delta T \tag{6.4}$$

As we know ΔT for no airflow from table 6.9 and 6.10 we can calculate a for the two panels:

$$a_{(ECscan)} = \frac{15}{36} J/°\mathrm{C} \cdot s \tag{6.5}$$

$$a_{(Var1)} = \frac{15}{35} J/°\mathrm{C} \cdot s \tag{6.6}$$

Combining (2) and (3), this time with a non-zero convective heat transfer component, gives:

$$\Delta Q_t/\Delta t = 15 - a \cdot \Delta T \tag{6.7}$$

Substituting a from (5) into (6) allows for calculating the energy that is lost through convective heat transfer.

$$\Delta Q_t/\Delta t = 15 - \frac{29 \cdot 5}{12} J/s \tag{6.8}$$

Thus, the heat lost through the ventilated air for the EC panel in fan set up A is 2.92J/s. Results for all fan positions is shown in row "measured" in table 6.11 and 6.12 for EC panel and variant A, respectively.

Enthalpy of equivalent flow

As we know the equivalent flow of the different scenarios, it is possible to calculate the energy required to heat up this volume of ventilated air, which can then be compared to the previous results. The required heat to bring the ambient air up to the temperature of the test chamber air can be expressed as:

$$dh_{A-B} = c_{pa}(tB - tA) + xc_{pw}(tB - tA) \tag{6.9}$$

where c_{pa} is the specific heat capacity of dry air (1.005kJ/kg*K), c_{pw} is the specific heat capacity of water vapour (1.84 kJ/kg*K) and x is the mass ratio of water per air (0.003 kg/kg). The heat capacity of water is therefore irrelevant, and the equation can be simplified as:

$$dh_{A-B} = c_{pa}(tB - tA) \tag{6.10}$$

Tables 6.11 and 6.12 show the calculated and measured heat losses for the two panels.

	Fan position and speed					
	X	Z	A	B	C	D
Calculated	0	0.137 J/s	2.97 J/s	2.42 J/s	2.88 J/s	6.48 J/s
Measured	-	1.25 J/s	2.92 J/s	2.50 J/s	3.75 J/s	6.67 J/s

Table 6.11: EC scan panel: heat loss through forced convection. Upper values theoretical values calculated from equivalent flow, lower values actual measured heat loss. Fan position as in table 6.10.

	Fan position and speed					
	X	Z	A	B	C	D
Calculated	0	0.131 J/s	2.60 J/s	-	-	5.33 J/s
Measured	-	0.430 J/s	2.14 J/s	-	-	7.29 J/s

Table 6.12: Variant A panel: heat loss through forced convection. Upper values theoretical values calculated from equivalent flow, lower values actual measured heat loss. Fan position as in table 6.10.

Heat transfer between panel and ventilated air

Figure 6.10a shows CO_2 concentrations and temperature of the chamber. The cooled panels was attached to the chamber at 80 s, the CO_2 introduced at 150 s and the fan was turned on at 270 s. As soon as the cooled panel is attached, the temperature in the chamber starts to drop. This is momentarily counteracted by the introduction of warm, CO_2-rich air, but the lowering of temperature resumes when no more air is introduced via a continuous flow. The fan, which servers to rapidly ventilate the elevated levels of CO_2 does not significantly heat the air in the chamber, though there is a long term warming of the chamber, presumably due to the progressive absorption of heat energy by the panel from the ambient air. The inner chamber reaches a minimum temperature of -2.5 °C after approximately 15 minutes. The results for panel variant A are similar, and shown in figure 6.10b.

Evaporation and cooling of ventilation air

The relative humidity of the chamber air increased rapidly with a corresponding drop in dry bulb temperature. Minimum temperature of 22.3°C was reached at 1900 s, approximately 30 minutes after the fan was turned on, and with a corresponding RH of 73%. According to figure 3.5 this humidity should correspond to a temperature of 20.8 °C, the difference is likely due to heat transfer through the chamber walls which also explains why the temperature after 1900 s increases slightly even though RH is increasing. There was little difference in the behaviour between the two panels (figure 6.11).

6.3.3 Interpretation of results

The results of the first experiment in this section indicate that the ambient temperature was not dominant in determining the temperature in the test chamber, as they do not equilibrate in the manner the CO_2 concentration does. Due to the high sensible heat of the solid materials relative to the air, this likely means that the air and solids equalise in temperature more rapidly than colder air is introduced. A second potential explanation is that the flow of heat is somehow decoupled from the flow of concentration (which would disprove hypothesis K). This is fully tested in the second experiment, which shows that the heat loss in a steady state system is the same as would be expected from the equivalent flow, showing hypothesis K to be true.

Experiments 3 and 4 show, together with the first, that hypothesis L is correct, and in all scenarios the temperature or moisture level equalise between the surfaces and the air at a faster rate than the rate with which new air is introduced.

Specifically in the fourth experiment it is found that significant evaporation takes place from the wet solid surface into the airstream. The evaporation leads to a reduction of the internal temperature of the chamber, in accordance with what would be expected from a direct evaporative cooling system as described in chapter 3.

6.4 Conclusions

In this chapter has been established that panels perforated with a large number of small channels, when exposed to an external turbulent airflow but without a net cross flow, can facilitate a significant mass transfer between the two sides of the panel. This mass transfer is of a similar magnitude to the flows which have been recorded in chapter 4 where they were induced by a regularly oscillating airstream. The important characteristic of this flow, and which distinguishes it from any leaky building, is that it is a 0-net bulk flow, with no cross flow, i.e. a mean of ventilating a dead zone with no significant increase of internal air velocities.

It has however been found that the hypothesis that this mass transfer is caused by the interaction of the reticulation of the tunnel network and geometry and the naturally occurring wind, is incorrect: there appears to be no strong correlation between the panel topology and the mass transfer rates in identical forced convection scenarios. It is therefore likely that the mass transfer occurs because the external eddies and turbulence penetrates the wall, rather than being generated within it from oscillations.

The lack of correlation is, however, a significant finding, as is could be expected that the increasing static flow resistance of the EC panel relative to variant A would influence the mass transfer to a similar degree. This suggests that the reticulated geometry is acting as a discriminatory barrier, allowing transient flows to pass while inhibiting static flows. In addition, it is likely that the turbulence would be inhibited by long tunnel passages, and that extending panel A to a greater thickness would have a proportionally greater impact than what was shown for panel D.

Furthermore, it has been shown that the heat loss associated with the transient air mixing is the same as would be expected from a steady, laminar flow of the same size as the equivalent flow. As it is unlikely that this energy can be recovered though heat exchangers or heat pumps due to the distributed nature of the air exchange, it becomes important how the air interacts with the solids of the panel, and these can potentially be used to condition the air or act as a thermal buffer. The experiments conducted show that this exchange is significant, as would be expected from a turbulent flow over a surface, and that the air fully homogenises with the solid surfaces in terms of temperature as well as moisture content.

The next chapter will explore different architectural devices which could be incorporated into a building, either as a mediator between the exterior and interior, or as fully internal devices utilising the mechanisms described in this chapter and the two previous.

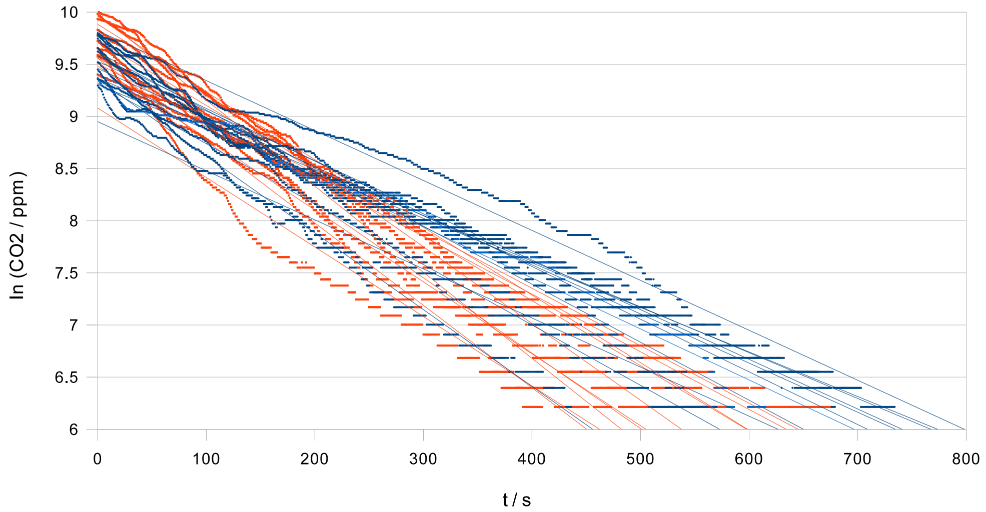


Figure 6.7: Comparison panel AC and A in outside wind conditions. Natural logarithm of CO_2 concentration tracking decay rate.

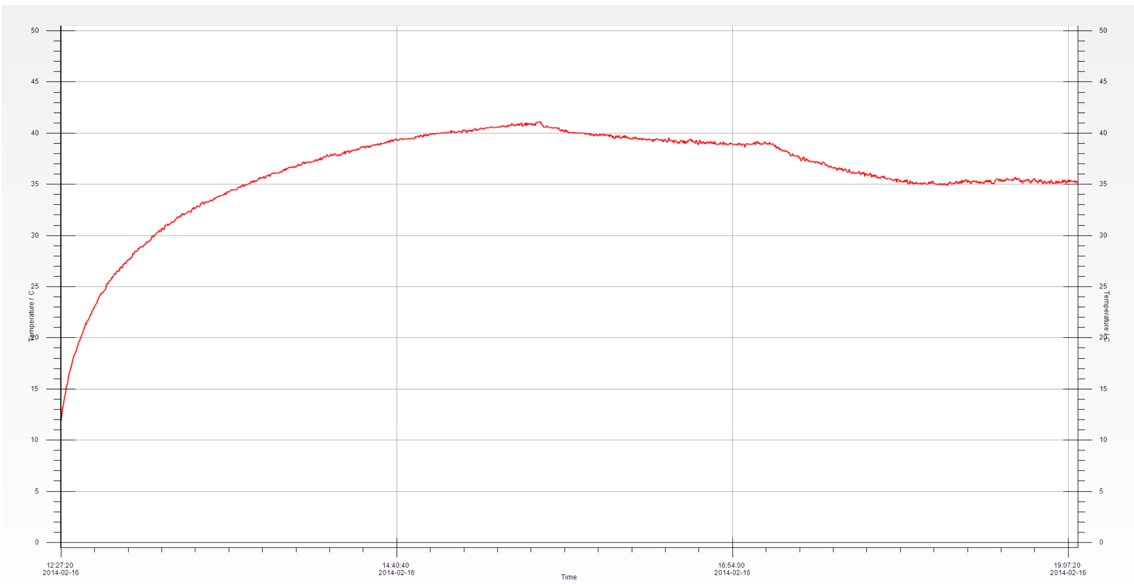


Figure 6.8: ZA3: Typical raw data from steady state temperature measurement.

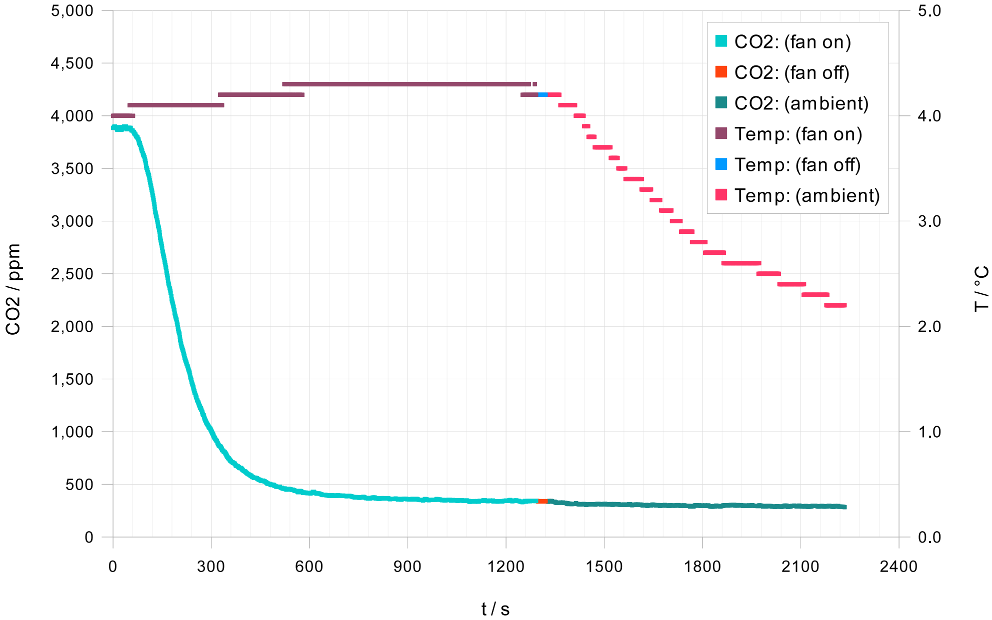
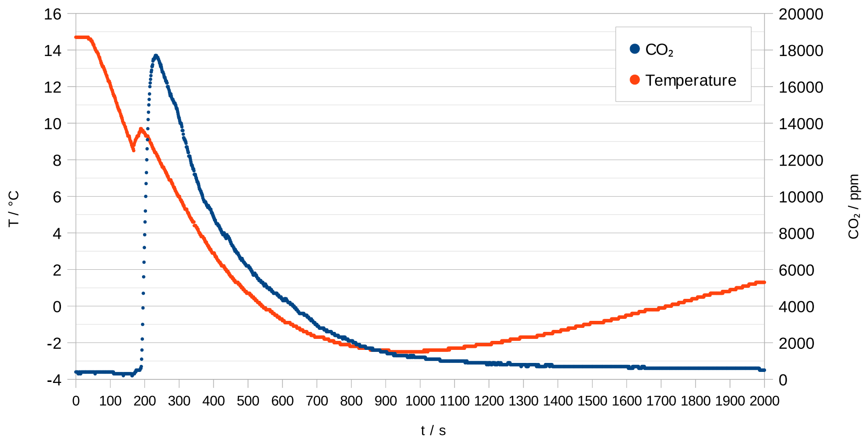
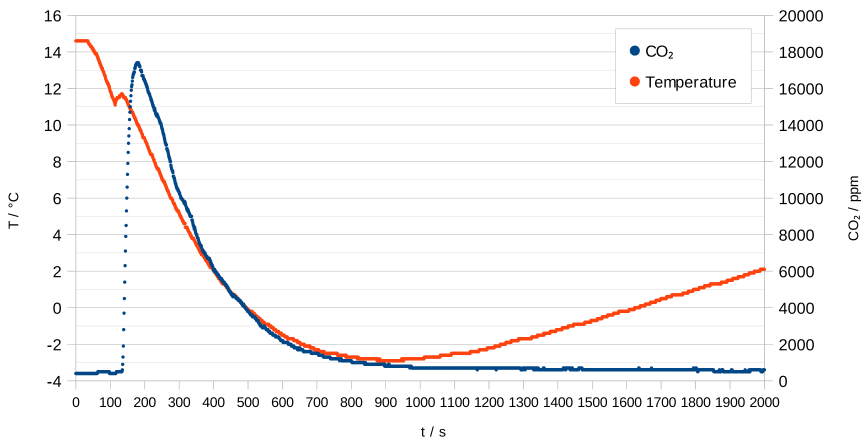


Figure 6.9: Simultaneous measurement of CO_2 concentration and temperature within test chamber while fan was running. EC scan panel used. Fan was turned off at 1300s, sensor was moved from test chamber to ambient air at 1320s.

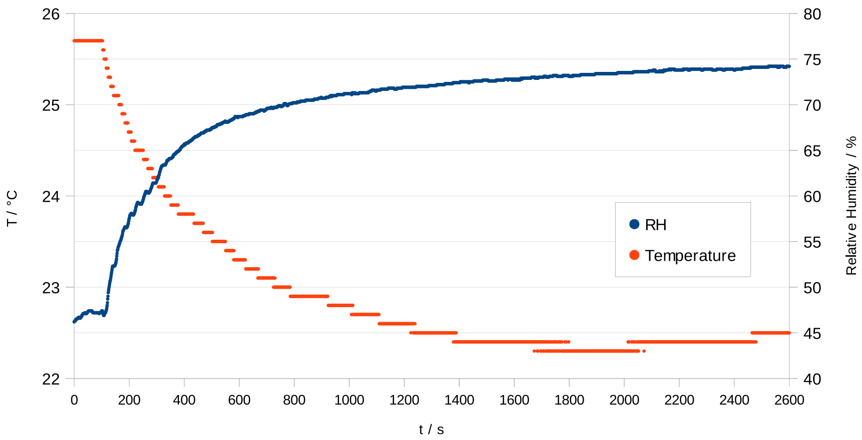


(a) Panel EC

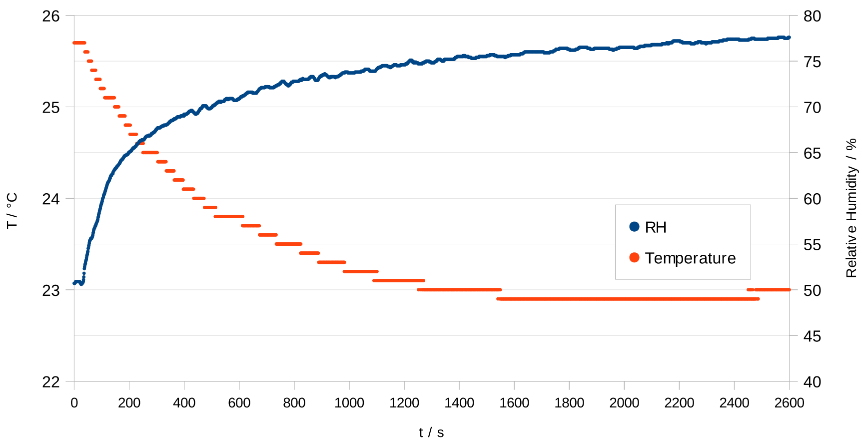


(b) Panel A

Figure 6.10: Ventilation across cooled panel. Ambient temperature 14.6 °C, panel cooled to -18 C.



(a) Panel EC



(b) Panel A

Figure 6.11: Ventilation across water saturated panel. Ambient temperature 25.7 °C, ambient humidity around 45-50%.

Chapter 7

Architectural Application: Structural Integration of Transient Processes

Performance-oriented architecture is based on the understanding that architectures unfold their performative capacity by being embedded in nested orders of complexity and auxiliary to numerous conditions and processes: such architectures are essentially non-discrete.

– Michael Hensel[1]

7.1 Introduction

Chapter three describes a number of technologies which are employed to regulate the internal climate of dwellings and other buildings. A number of these are ventilation systems, and the others are intended to regulate temperatures or humidity. Almost exclusively, they either rely on passive transfer, i.e. naturally occurring internal convection and conduction, or on steady bulk flows, either natural or fan-powered. This thesis proposes that the transient mass transfer mechanism described in the previous chapters can be used to improve the performance of some of these systems, and to provide means to integrate similar functions in the building envelope or other structural parts. The transient mechanisms are not necessarily direct replacements of the more conventional flows, but should rather be viewed as a complement, a way of increasing the toolbox available to the designer, and which in certain situations can provide significant benefits.

[1] (Hensel 2013, p.31)

The tortuous networks which have been described and make possible the transient mass transfer are distributed, with a multitude of small tortuous channels, which in turn means a large surface area. This configuration is such that the exchange between solid and fluid will be maximised, a condition which is further enhanced by the turbulent nature of the flow. Such geometries are not well suited for steady flows, as the pressure drop can be significant, and it may be difficult to ensure a clear path between inlet and outlet without inadvertently creating 'short-cuts'. On the other hand, the transient mass transfer is the result of mixing of gasses, and will not work well over large distances, where it may be preferable to create combinations of steady and transient flows, or to introduce the oscillations in a non-zero net flow.

The results in the previous chapter show that the transient mass transfer over the reticulated tunnels can be, at least partially, driven by naturally occurring wind. This provides a mechanism for natural ventilation in a true permeable envelope, or to drive other types of heat or mass flows, which in the right condition allows the system to exploit ambient wind energy. It is not clear how these mechanisms relate to each other in the context of the termite mounds, and further research may provide mechanisms for how ambient energy may be utilised in more efficient ways, which is addressed in greater depth later. The active system, where the turbulence is generated internally has the benefit of full controllability, including the potential mean to control, via the frequency and amplitude profile of the oscillations in combination with a spatially varied tunnel network, the specific location in the structure where the mixing occurs.

The potential to implement these transient systems is separated into two categories: direct and indirect. Direct refers to systems where the movement of air is the end in itself, i.e. ventilation scenarios. This is addressed in the section directly following this introduction, *Natural ventilation through distributed permeability in building envelopes*. After this follows a section, *Activated Flux Structures*, which instead focuses on the transfer of heat and mass as secondary effects of the air flow, and which can allow the designer to influence the temperature and humidity of the indoor spaces.

7.2 Natural ventilation through distributed permeability in building envelopes

A ventilation solution based on distributed and tortuous permeability is considerably different from a conventional mechanical ventilation system or natural ventilation, though there are some similarities between transient ventilation and vernacular natural ventilation solutions. The transient ventilation can be understood as a mixing of the air masses inside and outside of the wall: in an ideal scenario there is no net bulk flow across the wall, and thus the indoor air velocity is unaffected. A net flow of gasses, energy or particles will, however, take place where concentrations or properties are different at the sides of the wall and a gradient is present, allowing fresh outdoor air to be introduced to the building. The system proposed in this section is primarily passive or natural, the mixing of fluids and consequential mass transfer is caused by turbulence which is found in or generated by natural wind flows. Figure 7.3 (a) and (b) illustrate the organisation of such a permeable wall.

As the transient ventilation only affects the air volume closest to the wall surface (experiments indicate that the air volume that is within one or a few decimetres from the wall is effected), internal mixing of indoor air is a requirement. It is however likely that the slight air movements and turbulence that arises from human activities, convection from heating, and local pressure variation is sufficient for this to not be a limiting factor - perfect mixing of internal spaces is often assumed when calculating ventilation rates, see e.g. Sherman (1990). Because of the lack of geometric constraints on such flows, they are low velocity, low energy flows whether naturally present or induced, limiting problems of noise or draughts which can be associated with conventional ventilation.

The network of tunnels which permeates the building envelope in order to achieve the transient ventilation can be located in any part of the building envelope (see design guidelines and constraints below), and can potentially be integrated into continuous sections or zones of the envelope. In order to simplify the description and concept these zones are referred to as *transient ventilation panels (TVPs)*. All data and description applies equally to a permeable structure which is simplified to a discrete panel component or to an integrated solution which is part of a continuous building envelope and/or structure.

Benefits of transient ventilation

The transient mass transfer offers a number of advantages over conventional ventilation, whether natural or mechanical. However, the proposed systems are not necessarily meant as a direct replacement of conventional ventilation, but as a complement or alternative, which acts in different ways and dependent on situation may offer an advantage over other mechanisms.

The primary significance is that the transient mass transfer offers flow in and out of a dead zone - a sealed area with essentially only one opening which limits or prevents cross flow. This is distinct from conventional ventilation which relies on an inlet and an outlet, or leaky building envelopes which are leaky all around, and where external pressure differences can cause significant and uncontrollable flows in the building and envelope. As such, the transient ventilation causes no significant elevation of indoor air velocities and maintains a high level of controllability. In the case of other openings in the building envelope, the high flow resistance of the tortuous passages limits or dampens external wind gusts, decreasing their impact on internal climate relative to other openings such as windows.

The TVP's act as a filter in this manner, limiting continuous flows, but allowing certain transient flows to pass. The reason for this limiting effect is the significant contact between the TVP surfaces and the air which passes over it. This can also be used to condition the incoming air, which is addressed in length below, and by acting as a particle filter, trapping larger airborne particles as they impact the surfaces and preventing them from passing the TVP to the building interior.

As the system is partially natural, it allows for energy savings compared to mechanical ventilation, while maintaining the possibility to selectively assist the natural ventilation in case of weak winds. In addition, the system primarily relies on the geometry of the walls or panels, and lacks complex multi-part components and moving parts, facilitating local manufacturing and minimising wear.

The final benefit of the permeable panel may lie in the experiential qualities, allowing sounds, scents and light to pass through in ways and combinations which are not possible with conventional building technologies. This aspect remains unexplored in detail however, and full scale tests would be needed to understand these aspects.

Minimising net bulk flow

When large scale pressure differences take place across the wall, a bulk net flow will occur (this is the type of flow utilised in conventional natural ventilation strategies), which will limit or negate the benefits of transient ventilation and should therefore be avoided. These pressure differences will almost always be present between the different sides of a building – which is utilised in cross flow ventilation (Mochida et al. 2005) – and often between different areas of the same wall – which is used in single sided ventilation (Warren and Parkins 1985). For the latter the pressure differences are larger the bigger the wall, and are enhanced by geometric features on the wall such as corners and protrusions (Khan, Su and Riffat 2008). If there is an unobstructed connection between these areas of different pressure, a net bulk flow will result.

In order to minimise these leaks, a number of design guidelines become important (figure 7.1.

1. The ventilated zone (either a whole building or a smaller compartment such as a room), needs to be sufficiently airtight in all parts of the envelope apart from the TVP in order to minimize potential cross flow. As is described in chapter 3, building airtightness standards have been rapidly developed in latter years, and current techniques are most likely more than sufficient for what is needed.

2. Each ventilated zone should have permeable envelope components facing a single side of the building.

3. The permeable envelope section of each ventilated zone should be as compact as possible, and extend perpendicular to permanent pressure gradient rather than along.

4. The permeable envelope sections should be placed in areas of spatially continuous pressure. This means sudden geometric variations in the permeable envelope should be avoided.

5. Multiple ventilated zones should be connected via airtight doors/barriers which are opened and closed quickly.

In addition to these guidelines, the geometry of the perforations can be selected to create maximum flow resistance. The experiments in section 4.4.1 demonstrate that tortuous and reticulated geometries have a higher flow resistance to static flows than the simpler geometries, while exhibiting no loss or in some cases a gain in transient permeability.

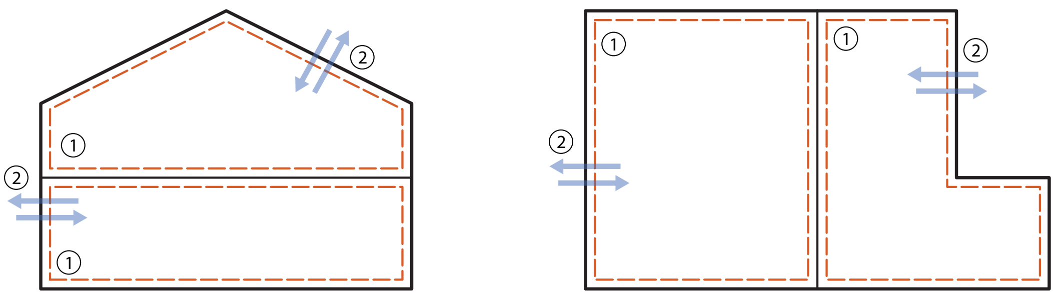


Figure 7.1: Each airtight ventilation zone (1) is ventilated through a single permeable zone in the envelope (2), located to avoid large scale pressure variation.

7.2.1 Capacity and dimensioning

In order to establish the permeable envelope area needed to ventilate a given volume, the results from the natural wind exposure tests in chapter 5 provide the following numbers (which are based on a moderately windy scenario with average wind speeds of 11 m/s). For the EC scan panel, the equivalent flow was found to be 0.06 l/s. The permeable area of the panel front is 0.04 m^2. This translates to a flow of 5.4 m^3/m^2/hour. Based on statutory requirements of 0.5 airchanges per hour for residential buildings, this indicates that each m^2 of permeable envelope is sufficient to ventilate approximately 10 m^3 of living space, assuming adequate internal mixing.

A caveat is that the mixing rate may not scale proportionally when the area and volume increases. If the scaling is less than 1:1 the overall ventilation rate decreases with larger areas. This seems unlikely, but could be caused by poor internal mixing, which is a greater risk in larger spaces. If the scaling is higher than 1:1 however, the ventilation capacity increases. A likely mechanism why this may happen is temporary net flows, essentially short duration jets, which can arise from pressure events taking place at a short temporal scale (pressure events taking place over longer temporal scales cause draughts and should be avoided as has been previously outlined.) These are more likely to happen the greater the area of permeable envelope, and could therefore affect the scaling.

The measurements above are based on a wall thickness of approximately 50mm, thicker walls will decrease the transfer rates as the turbulence generated from the wind will lose energy at deeper penetration depths. The results of the wall thickness dependency tests in the previous chapter indicate that the drop off in ventilation rate is less than would be expected from a 1-to-1 linear relationship with wall thickness: in the test a 200% increase of thickness to 150 mm led to a 58% decrease in mass transfer (relative to a 67% decrease which would have been expected from an inverse proportionality). It is likely that the effect of the wall in terms of diminishing flow can be at least partially compensated through active oscillation assistance. Similarly, other modifications of the wall geometry is likely to affect the mass transfer rates, for example by increasing the total porosity and the combined cross section area of the air channels. The effects of such modifications have not been further explored.

7.2.2 Oscillation assistance

While is is possible to create an entirely passive TVP, this would be dependent on beneficial wind conditions. Too little wind would reduce or eliminate the mass transfer; too much would cause unnecessary heat loss and potential disturbances. It is therefore desirable to embed an oscillator within the TVP. This can act to increase the flow when the outside conditions are too still, or when extra flow is needed. In addition, this allows the wall to be made thicker which decreases the potential 'leaky' undesirable flow. Figure 7.3c demonstrates the possible location of such an oscillation device within the TVP

7.2.3 Conditioning of incoming air

As was demonstrated in the previous chapter, the air that crosses the perforated wall interacts strongly with the solid, equalising its temperature and readily picks up excess moisture. The reason for this is evident in the figures presented in chapter five (figures 5.3 and 5.8), where the turbulent nature of the flows in the reticulum leads to internal flows in all directions, including parallel to the normal of the adjacent surface, allowing for a significantly greater exchange between the solids and fluids. This provides a method for conditioning the incoming air by means of the wall solids, e.g.

by embedding pipes in the walls or other parts of the envelope where the TVPs are found which can carry heated or cooled water into the structure. Considering a digital fabrication scenario, these pipes can be fully integrated in the walls by means of manipulating the internal wall geometry. If water leakage is a problem, the embedded channels could be lined with a different material, impregnated with a secondary material which seals pores[2], or applied with a higher density in order to reduce permeability. It may also be feasible to embed resistors and electric wiring in order to heat the wall electrically, but his is generally the solution least desirable from an energy conservation perspective.

The potential porosity and wicking ability of the material can also be exploited however, in order to integrate a system of evaporative cooling in the wall. Experiment results and literature indicate that this could potentially lower the temperature of the incoming air by 3C assuming outdoor relative humidity of 50%, and potentially significantly more at lower RH (see figure 3.5; 35C at 20% RH is equivalent to 23C at 70%. These values assume direct evaporative cooling, but as the air flow in the wall is not unidirectional it acts as a hybrid direct/indirect system. This is due to the evaporation from the wall surfaces where the resulting humidity is returned to the outside and removed by winds currents. It may be possible to increase the ratio of indirect to direct evaporative cooling by wetting the outer half of the wall to a significantly higher degree than the inner half of the wall, which would enable the efficient operation of such a cooling system in more humid climates, as well as reducing or eliminating the increase in internal humidity (Givoni 2011).

Humidifying the air carries obvious benefits in dry climates, but the inverse can also be done. If the wall is made from an absorbent material, such as clay (adobe), it can absorb moisture from the air if the relative humidity is greater than a threshold, and maintain the air at this RH as long as the clay is not saturated. Materials with high sorption potential will often have low wicking potential, which means careful consideration has to be placed on the desired properties of the wall. This, however, also increases the ability to create a functional wall with significant adaptation to the prevailing micro-climate.

7.2.4 Thermal buffering over diurnal cycles

An alternative to the active conditioning, the TVP can be made so that the panel material act as a buffer, redistributing the heat of the incoming air over the diurnal cycle. This could provide an heat recovery mechanisms similar to counterflow heat pumps in mechanical ventilation systems, though it is only possible in cases of significant diurnal temperature variation. In such climates, buffering effects could contribute to an agreeable indoor climate without the reliance on advanced HVAC systems and associated cost and energy consumption. The solution is particularly suitable to climates where the average daily outdoor temperature is close to desired indoor temperatures but where the daytime is too hot and the night time too cool.

Figure 7.2 shows the annual average diurnal temperature range. Many regions of the world, particularly in and near the subtropics exhibit diurnal temperature variations of 15°C or more. Notably these conditions are found in arid, hot and high-altitude regions. Several densely populated regions fall within the category, notably Western USA, Mexico, Australia, Northern and Southern Africa, and large parts of Central Asia. Within these regions are several population centres which are rapidly growing and experiencing significant economic development, and where finding high

[2] A vernacular example is *Tadelakt*, where olive soap is used in combination with surface smoothing to waterproof lime mortar (Wolff, Diederichs and Ait el Caid 2014)

comfort alternatives to air conditioning can lead to a significantly reduced future environmental footprint.

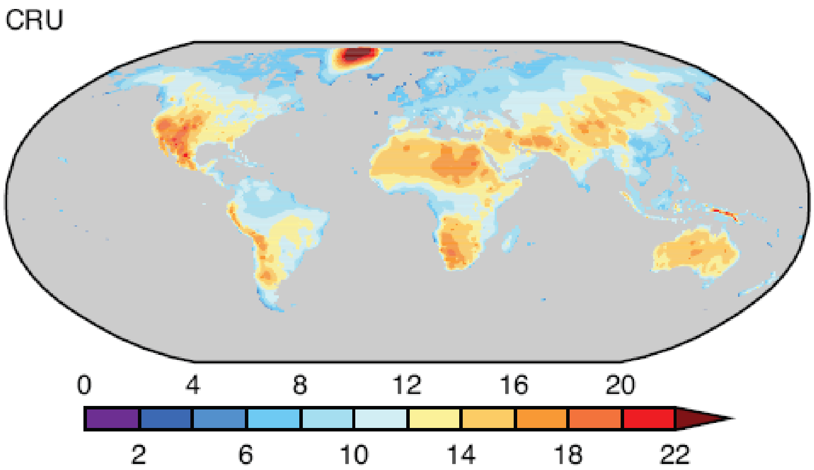


Figure 7.2: Annual average of diurnal temperature range over land. Adapted from Randall et al. (2007).

For such a model to be effective, the wall must be able to store an amount of thermal energy over a 12 hour period which is significantly larger than the energy that is absorbed to or from the traversing air, and to any losses/gains to the outside (if these are equal or if the thermal capacity is smaller than the losses, the solution will still provide some benefit, though much less than the full potential). This depends on three parameters or factors: the total thermal capacity (latent and sensible) of the wall, the volume of flow over this time period, and the losses to the outside though radiation or conduction.

Thermal balance calculations

The thermal storage capacity of a solid wall is described by equation 7.1 where Q is the heat transferred to or from the system, m is the mass of the wall, c_p is the specific heat capacity of the material and ΔT is the change in temperature.

$$Q = m \cdot c_p \cdot \Delta T \tag{7.1}$$

Equation 7.2 shows the mass of the wall per m^2 for length l, porosity ϕ and density rho.

$$m = l \cdot (1 - \phi) \cdot \rho \tag{7.2}$$

Assuming 100mm wall thickness, terracotta material ($c_p = 900J/(kgK), \rho = 1700kg/m^3$), and 20% porosity, the thermal storage capacity of a wall is $122kJ/(m^2K)$. For a wall made from a stone or concrete material ($c_p = 880J/(kgK), \rho = 2400kg/m^3$) the thermal storage capacity is $169kJ/(m^2K)$. The thermal mass of a number of wall materials and thicknesses is shown in table 7.1.

The equations are similar for the air that flows across the wall, except the volume is given in section 7.2.1 as $5.4m^3/m^2/hour$. Dry air has a density $\rho = 1.1839kg/m^3$ at 25°C and a specific heat capacity $\phi = 1006 J/(kgK)$. The thermal mass of the air the passes through the wall is therefore $6 kJ/(m^2K)$ per hour, or $72 kJ/(m^2K)$ over a 12 hour period.

Based on these numbers and the rapid rate of thermal transfer shown in figure 6.10, the proposed wall should be able to provide significant conditioning of the air in climates there the daily temperature variations span across a reasonably comfortable daily mean temperature.

Material	Thickness (mm)	Heat Capacity ($kJ/(m^2K)$)
Concrete	100	169
Concrete	200	338
Terracotta	100	122
Concrete with 5% PCM	100	1200

Table 7.1: Thermal storage capacity for varying wall material and thickness.

Minimising waste heat gain

The Wall will however not only gain heat from the air passing through it, but also directly from solar irradiation and the outside air which comes in contact with the wall surface. In order to minimise this loss which may be significant, it is proposed that the outer layer of the wall is made from a material with low heat conductivity. This may be a layer of insulation, or by manipulating the micro-porosity of the material thereby reducing its conductivity and heat capacity.

In order to calculate the heat gain from this source, the wall's U-value can be calculated. For a 100 mm thick wall, the wall mass will have an average distance to the outer surface of 50 mm. Concrete has a conductivity of $1.28 W/(mK)$, and EPS insulation $0.037 W/(mK)$. Based on these numbers, the heat gain without insulation is $4.56 W/(m^2K)$, and with 20 mm insulation $1.32 W/(m^2K)$ (10 mm insulation yields $2.04 W/(m^2K)$, 50 mm insulation yields $0.64 W/(m^2K)$).

This is equivalent to $4.7 kJ/(m^2K)$ per hour, or $57 kJ/(m^2K)$ over a 12 hour period. This equals 80% of the heat gained from the ventilation air (thus a 55% efficiency), and the total (external loss + heat transferred to air ventilation air) is well within the thermal buffer capacity of the wall.

If the insulation is of a less efficient material such as aerated concrete or wood with a thermal conductivity of $0.13 W/(mK)$, the heat gain from the outer surface becomes $2.68 W/(m^2K)$ which equals $114 kJ/(m^2K)$ over a 12 hour period, which would exhaust the buffer capacity in less than 12 hours, and reduce the effect during much of the cycle due to the gradual warming of the wall. Using no insulation, which may be preferable from a cost and fabrication perspective, would increase the loss to $16.4 kJ/(m^2K)$ per hour, or $196 kJ/(m^2K)$ over a 12 hour period (Table 7.2 shows the heat gain in a number of insulation scenarios). In this case the wall would not be very effective at reducing indoor temperatures.

If the cost or practical constraints prohibit the addition of an insulating layer, an alternative strategy is to increase the heat capacity of the buffer medium. Doubling the thickness of the wall would increase the thermal capacity linearly to 200% of initial. A 200 mm thick wall would have a thermal capacity of $338 kJ/(m^2K)$, sufficient to provide adequate buffering without an insulating layer. If thickening the wall is not possible, embedding Phase Change Materials (PCM) in the wall material can significantly increase the thermal capacity, and has the added benefit of clamping the wall temperature at a fixed and very narrow range. Entrop, Brouwers and Reinders (2011) cites manufacturer specifications of embedded waxy PCM in the form of micro granules. These have a latent heat capacity $c_l = 110kJ/kg$ at $23°C$, and can be used at a ratio of 5% in concrete, which increases the thermal capacity of the concrete by a factor of 7 to $1200kJ/(m^2K)$.

Insulation Material	Thickness (mm)	Heat gain/loss ($kJ/(m^2Kh)$)
none	0	16.4
EPS	10	7.3
EPS	20	4.7
EPS	50	2.3
Porous Stone	20	9.6
Wood	20	9.6

Table 7.2: Heat loss/gain through external surface - 100mm concrete wall with varying external insulation.

7.2.5 Geometry and typical drawings

For a passively driven system, it is demonstrated in chapter 6, figures 6.6 and 6.7, that the specific topology of the tunnel networks is not of critical importance for determining the total ventilation rate, but rather the total cross sectional area. However, in order to facilitate induced turbulence through oscillation, the geometry needs to follow the reticulated parameters documented in section 7.3.1, which also adds the benefit of the high flow resistance of such geometries.

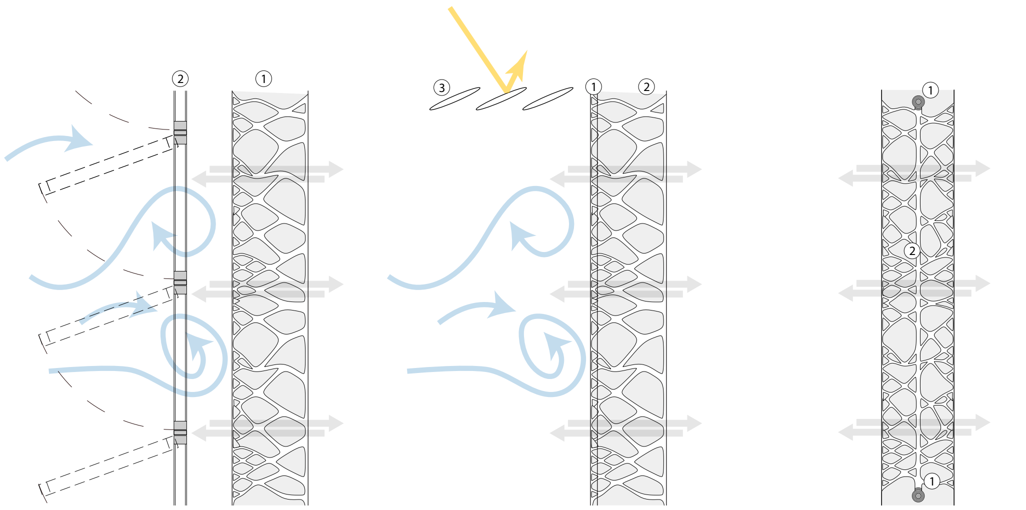
It is speculated that the termite mound may utilise resonance effects, where the long channels called the surface conduits, which are connected to the inside of the EC in the termite mound, start oscillating at around 20 Hz. This may in that case lead to internal turbulence according to the mechanisms previously described, and would also require the described reticulation. This is an effect that could be used to enhance the wind driven potential of the TVPs, but further research is needed to understand how such a mechanisms could be structured, both with regards to the termite mounds and in full scale experiments.

While it may be possible to achieve adequate effects with a number of network configurations, it is suggested that the solutions for transient ventilation are based roughly on the measurements taken from the termite mound EC, as these have consistently been shown to behave well in a large number of scenarios and to balance various costs and benefits. The channel radii found in the termite mound EC are in the range of 3-5 mm in the outermost portions of the EC, with a gradually increasing radius towards the inner spaces. Experiments conducted and described in chapter 5 suggest that an equally dimensioned network is at no disadvantage when using induced flows. However, the data also suggests (though tentatively) that a more diverse network may be able to collect a larger portion of the energy available in the wind, which is found at a wide frequency spectrum. The edge length of the networks varies between approximately 8 and 30 mm, with the larger dimensions being associated with wider tunnel radii. The outer surfaces have a permeability of about 5%, distributed over approximately 4,000 openings per m^2.

Building implementation scenarios

Figure 7.3 demonstrates how a TVP may be implemented in a building envelope. Section (a) shows an implementation which incorporates a secondary skin on the outside of the TVP which makes it possible to limit, partially or fully, the flow across the envelope through two mechanisms: to reduce the amount of outside turbulence which reaches the TVP itself, and by providing a limit to the mass transfer between the outside air and the outer surface of the TVP. This implementation is suited for climates where the heat loss associated with the distributed ventilation is unacceptable during parts of the annual or daily cycle. While this solution can only complement another ventilation system, it can provide significant benefits to the interior space by allowing scents, sounds and fresh air from the outside to penetrate the walls. The solution shown in section (b) is based on the system outlined in section 7.1.4, and incorporates a layer of insulting material on the outside of the TVP as well as optional shading devices. This is the solution appropriate for climates with large diurnal temperature variations. As has been shown above such a system is capable of creating large comfort benefits in suitable climates. Section (c) demonstrates how an system for oscillations assistance can be integrated into the TVP, which would in most cases be used in combination with the other configurations.

Furthermore, figure 7.1 demonstrates how TVPs should be placed in the building envelope relative to internal ventilation zones, in accordance to the guidelines outlines in section 7.1.



(a) Double envelope TVP **(b)** Heat buffering TVP **(c)** Assisted TVP

Figure 7.3: Potential implementations of Transient Ventilation Panels (TVP). **(a)** A secondary skin outside of the TVP allows for the elimination of any air flow, transient or bulk, across the TVP. **(b)** The addition of a thermally insulated layer at the outside of the TVP allows, particularly when used in conjunction with a sun screen, a diurnal thermal buffering of the incoming air. **(c)** The integration of oscillating membranes into the TVP enable an assisted mode where the panel functions at increased capacity in the absence of sufficient wind.

7.2.6 Transient ventilation summary and conclusions

Based on the research conducted, it is possible to create a distributed ventilation system, which relies on transient, turbulent winds with zero net flow through the building, and which therefore cause no draught in the building internals and are free from fan noises. The lack of draughts can in certain scenarios be an advantage, though it may also be a disadvantage, particularly in hot climates where air velocity is relied upon to create thermal comfort.

Because of the distributed nature of the ventilation, it is not feasible to use mechanisms for central heat recovery (though mechanisms for local and distributed heat recovery may be possible to develop in the future). The system is therefore not suitable for very cold climates, unless it can be selectively turned on or off, for example by the means of a secondary envelope, or if the use and time negates the need for retaining heat.

The system relies on a high degree of airtightness in the other parts of the building envelope, and the specific placement of the permeable walls is critical to avoid cross-flows due to external pressure differences caused by wind direction. Large scale tests may reveal how the permeable wall effects the indoor environment in terms of acoustics, scents and perceived closeness to the outside – this may well have a significant psychological impact on the occupants and how they perceive their environment.

It is possible to achieve significant conditioning of the inbound air, either through the use of conventional heating/cooling systems distributed through water flows into the wall solids, where efficient transfer to the air flows take place, or through evaporative cooling. The latter has the potential in moderately dry and warm conditions to provide significant cooling potential at a very low energy cost. As is shown in table 3.3 there is significant potential for evaporative cooling even in many European conditions. With a digital fabrication process able to manage the high geometric complexity inherent in the permeable wall, the channels for water distribution can be easily integrated into the structure, eliminating the need for separate plumbing which causes expansion and compatibility issues because of varying material properties and joints.

Finally, the system has a potential for use in climates with a large variation between day and night temperatures. The ability to significantly buffer the indoor climate through the thermal latency of a solid wall can be a considerable energy saver in regions of economic development and rapid population growth. For the buffering to be effective, either a thin layer of insulation needs to be present at the outer surface of the wall, or the thermal storage capacity needs to be enhanced, either by increasing thickness or by the use of embedded PCMs in the wall material. If the buffering is fully effective, the temperature of the fresh air can be reduced with as much as 10°C at peak temperature, and increased as much during the coldest hour of night.

7.3 Activated flux structures

In a number of scenarios described in chapter 3, solids are used as storage of either latent/sensible heat or water. These systems are often simple buffering systems, which reduce the peak load during a cyclical period of some kind, but they can also be used asymmetrically, as for example in the case of night cooling ventilation. In all these scenarios the performance of the system is determined by two material properties: the thermal (or water) storage capacity, and the ability of that energy or matter to move between the storage medium (solid) and the air. Typically, these two properties are contradictory, which can severely limit the design possibilities from an engineering perspective. This is seen for example in PCMs which have a very large thermal storage potential, but where the thermal conductivity is low and often a limiting factor in system design. Similarly, large volumes have a high mass and therefore good storage potential, but because of increasing volume to surface ratios and longer average distances to the surface, the transfer rate between the solid and surrounding air is slow.

Zhang et al. (2007) have made a state of the art study of PCM materials, and and while the materials themselves have been significantly improved in later years, they identify three main areas which are in need of further research. These include methods for integrating PCMs in the building envelope, developing better heat transfer mechanisms (current transfer rates are a bottleneck for the efficient implementation of these materials), and combining PCMs with strategies for exploiting natural resources. Similarly, Padfield and Jensen (2011) has shown that the humidity buffering potential of end grain wood or unfired brick is held back by the transfer rates between the air and the bricks: only 4-18% of the total buffering capacity of an exposed unfired brick wall is accessible within a 24 hour cycle.

The solution to this issue is often complex geometries, where a highly folded surface increases the surface are and contact point between solid and surrounding air. This is seen for example in Lamberg and Sirén (2003), where fins are used to increase the surface area of PCMs and therefore the heat transfer rates, or in Padfield and Jensen (2011) where perforated bricks have a higher buffer value than solid bricks due to the increased solid – air contact. The problem with such geometries is that they tend to create dead zones with very low flow, caused by the dominance of boundary layers at such small scales. The conventional solution is the use of fans (as is done by Padfield and Jensen (2011)), but the flow resistance increases as the surface area and tortuosity increases causing such solutions to rapidly become noisy and energy demanding.

The the transient ventilation mechanisms described in previous chapters are not reliant on a net bulk flow, but rather generate or exploit a turbulence which creates greatly enhanced convection (diffusion + advection) rates. As has been demonstrated this flow is not limited by reticulated, narrow and tortuous channels.

The mechanisms for mass transport are dependent on an external energy source to generate the turbulence. In the systems outlined in the previous section this energy was found in the wind, but it is also possible to generate this turbulence internally from an oscillating accelerator as has been demonstrated in chapter 4. While this has an energy cost and a potential source of mechanical wear and failure, it introduces a level of control through the ability to selectively turn the flux on or off. This can allow for significant versatility and performance gains over conventionally passive systems while remaining simpler than a fan driven system. The combination of a single sided opening (dead-zone) which prevents cross-flow and high tortuosity and surface area which increases flow resistance, will limit air movements when the oscillations are turned off. In the absence of any major convention, heat flows will be limited to conduction/diffusion and the air will act as an insulator. The experiments conducted in chapter 4 indicate that the relative difference between mass transfer rates in activated and non-activated states are at least an order of magnitude, and likely it can be extended to significantly more in a full scale application where the longer distances and uniform internal temperatures can further limit forced and natural convection.

These systems can collectively be called *activated flux structures* (AFS), and are high surface, high mass structures where the geometry allows for control of the flux (of matter or energy) in and out of the solids through transient air flows. These are divided into two categories, thermal flux structures and moisture flux structures, though one could certainly imagine other flows operating through the same mechanisms.

7.3.1 Geometric design guidelines

The findings in chapter 4 and 5 indicate that the specific geometry of the egress complex is essential for the ability to induce turbulence and hence mixing from oscillations. Specifically, the reticulation of the networked channels play an important role in the phenomenon. The length of the node-to-node edges appears to dictate the stroke length, or amplitude of the oscillations required to generate the desired mass transfer. In addition, a greater macro-porosity (larger number of channels) allows for greater mass transfer.

The total mass of the system controls the potential thermal or mass storage potential (together with material properties such as specific heat capacity or micro-porosity), while the total surface area affects the interchange of mass or heat between the solid and the air. The latter is also effected by material thickness, and the heat or mass conductivity.

A final consideration is the ability of the structure to accommodate other design criteria or algorithms, which are dependent on other algorithms and demands, such as structural integrity, acoustic properties, passage of water conduits, etcetera.

The approach proposed for creating such structures is modelled on the geometry of the reticulated channel network found in the egress complex. Based on the results obtained in the previous chapters however, any geometric approach which incorporates the same (in kind) topology would behave in a similar way, and other approaches may be moire suitable in certain design contexts.

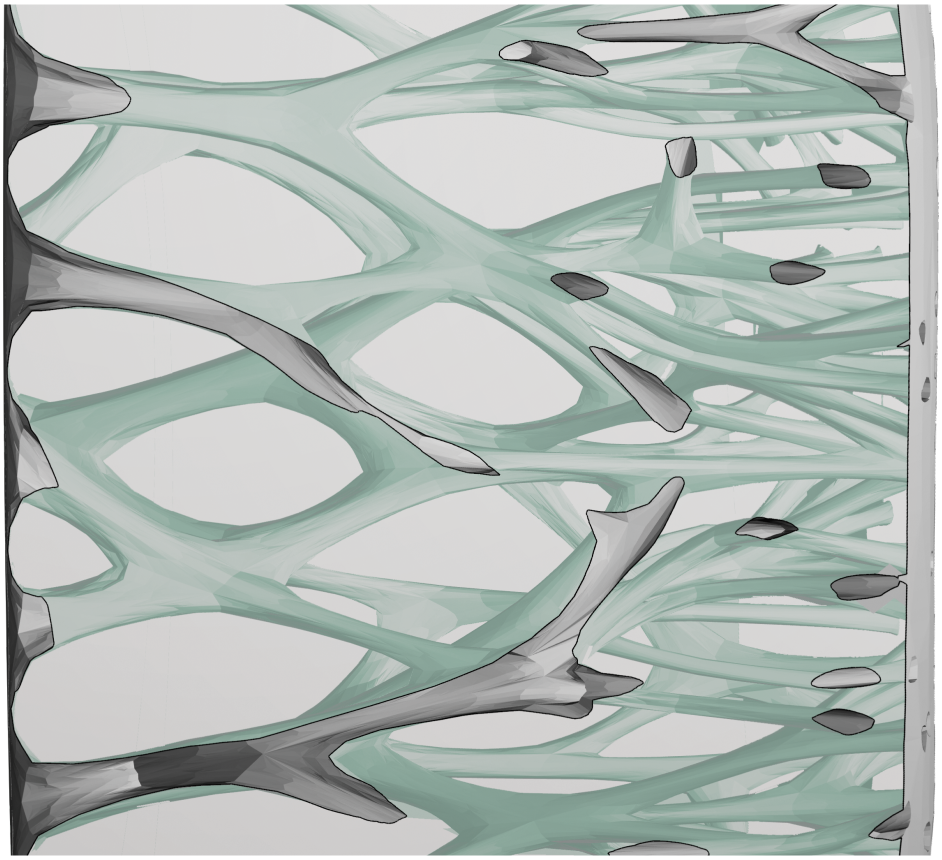


Figure 7.4: Wall section: internal structure of reticulated channel network (wall thickness 150 mm)

Reticulated channels

Figure 7.4 demonstrates an example of a reticulated network of channels passing through a solid wall section. This network was generated using a particle spring simulation based on the geometric data given in section 7.1.5, and the topological information given in chapter 4, figure 4.3. While it is fully feasible to generate such a network through manual design, such a hard-coded model is only suitable for generic panels meant to be standardised and mass produced. The benefits of the self-organising particle-spring system (or other algorithmic approaches) is its ability to adapt to any kind of geometric boundary conditions and constraints. As such it is suitable to integrated design scenarios of such nature which has been previously discussed, and where multiple variable design objectives need to be negotiated within a single continuous structure.

As long as the reticulation and approximate dimensions are maintained, the system is relatively robust with regards to the exact topology and geometry, and it is possible to make alterations to the induced oscillations after fabrication in order to achieve maximum efficiency. The exact nature of these dependencies are not fully investigated within this thesis, as such an exploration either requires the development of a full scale system, including fabrication strategies, or extensive mathematical research.

The flexibility of the geometry with regards to the relative position of the channels, gives this system its high redundancy and ability to adapt to variable design scenarios. The solid, through which the tunnels perforate, is continuous and therefore provides a large number of pathways for stresses to propagate through the material giving structural resilience and strength. It is also possible to 're-route' the channel network around obstacles and design elements such as piping, ducts, windows, etcetera.

These obstacles can potentially include a second tunnel network. This second network would be entirely separated through the wall solids, but otherwise potentially fully intertwined. This means an AFS components could have two, individually activated internal voids, which also could have different openings while maintaining the dead-zone condition (no cross flow). As both these air volumes would access the same solid, it would create numerous opportunities to move heat or moisture around while maintaining the airtight building envelope, for example as illustrated in figure 7.5 below.

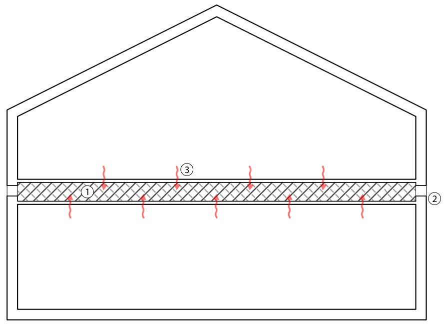
7.3.2 Activation oscillations

The oscillations which need to be induced to achieve the turbulent flow is modelled on the flow described in chapters 4 and 5. The two relevant properties are the amplitude and frequency of the oscillations. The effective frequencies have been found in the range of 10-100Hz, and it has been determined that the most effective frequencies are influenced by the resonant properties of the system as a whole. It is therefore advisable that the frequencies used are tested at the stage of full scale trials and adapted as required. Required amplitudes are in the region of 5 mm within the reticulated channels, the amplitude at the source is therefore dependent on the cross sectional area of the channel network measured perpendicular to the oscillation source and the free air orifice. Results from 2D experiments indicate that greater amplitudes can be used to compensate for a larger node-to-node distance in the reticulated network, which may be preferable due to fabrication constraints or other reasons. In the experiments the oscillations were generated through an oscillating speaker membrane requiring very little energy input, but the generation strategy for any application will be dependent on the scale of the system and other design parameters and is not addressed here.

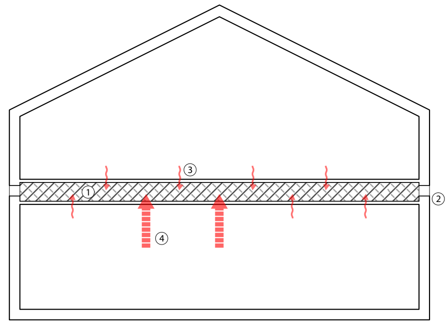
7.3.3 Asymmetric thermal storage

The ability to activate and deactivate flux in and out of solid storage media enables a wide range of architectural applications. Often these are already existing techniques which can gain a great deal of flexibility and usability through the increased control and the ability to achieve directed effects. The first one explored in this chapter is asymmetric thermal storage. This is not a new occurrence, with both traditional techniques such as night time ventilation or modern TABS systems being such examples, but many new design possibility are made possible without relying on expensive and demanding systems such as pumps and pipes.

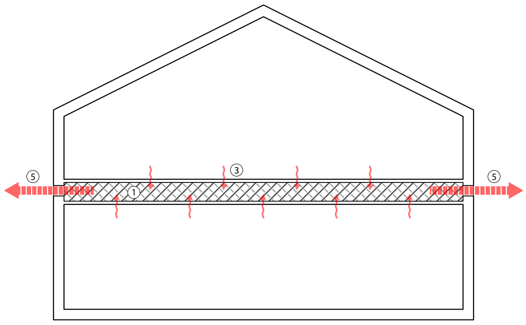
Buildings which utilize thermal mass for improving indoor climate are typically reliant on inertia to even out extreme temperatures, thereby improving thermal comfort and reducing energy



(a) Passive distribution of heat/coolth to building interior.



(b) Active distribution of heat/coolth to building interior.



(c) Active charging of heat or coolth to the storage medium from outdoor air.

Figure 7.5: Diagram showing the three possible states of the activated flux structure (AFS). (1): Storage medium / AFS. (2): Connection to outside air. (3): Passive absorption or release of heat to building interior. (4): Active absorption or release of heat to building interior. (5): Active absorption or release of heat to exterior air

costs by allowing heating and cooling systems to be designed for a smaller maximum load (or in the case of vernacular architecture where heating and cooling are less prominent, to reduce peak discomfort). In these application the thermal storage capacity is the dominant factor, and the rate of heat flux is not critical (the conductivity of typically used materials is sufficient even for deep, low surface area volumes over the relevant time scales).

However, if the flux rate could be significantly increased, the normal symmetry of the thermal buffering could be overcome, and the equilibrium temperature can be shifted towards one extreme or the other. This is the principle behind night cooling ventilation, which increases ventilation during the coolest time of the diurnal cycle (the night), in order to get rid of as much sensible heat from the building as possible, and then reduce the ventilation rate during the hot day time.

Activated flux structures can function as a thermal battery, which can be “charged” with sensible (or latent) heat or coolth during the favourable periods of the day or night. Such a structure would be constructed as a solid building component with high thermal mass, such as a slab or wall. This would be permeated with a reticulated tunnel network which opens up to the outside of the building. As described above, this air volume would exhibit little convection when inactive, but when the oscillations are activated the air inside of the mass would mix rapidly with the outside air, bringing the cooler (or warmer) outside air in contact with the thermal mass. This activation would last during the hours when the conditions are favourable, for example during the coldest early morning hours during summer, releasing the latent heat to the surrounding air. As outside temperatures rise, the oscillations would be deactivated, limiting the thermal interaction with the outside air. In this case slower conductive heat transfer and radiation would dominate, allowing the thermal mass to cool the interior of the building as the daytime temperature peaks. Inversely, the thermal mass could be activated during the warmest hours during winter or spring and autumn. Because of the asymmetry of the flow, the internal average temperature can differ from the external average temperature. If the depth of the system is great, and the distance between the mass and the outside air is large, as is likely the case if a slab is used as opposed to the building envelope, it is probably advantageous to combine the transient flow with a bulk transfer mechanism, either driven by external pressure differences or fans.

This model is based on a single internal network, connecting the thermal mass to the outside, while the thermal transfer between the inside air and the mass is conductive rather than convective, and therefore constant and slow (as most current thermal mass based designs). However, by introducing a second (or several) intertwined but not intersecting tunnel network which is connected to internal spaces it would be possible to control through convection the exchange of heat between the interior and the thermal mass as well. Then a previously accumulated store of sensible/latent heat or coolth can via transient activation be deployed during temporary and extreme load scenarios. This may include lecture halls or meeting rooms that require temporary cooling, or exhibition spaces which require open doors during cool evening hours.

Figure 7.5 describes the three states in which such a system can be. In figure 7.5a the flux is not activated, and the heat or coolth stored in the slab are gradually and slowly equalising with the building interior. In 7.5b the flux is activated, causing an increased exchange of heat between the slab and a specific part of the building interior. Finally, figure 7.5c shows how a flow between the slab and the outside air is activated in order to build up new potential heat or coolth.

7.3.4 Active control of indoor ventilation zoning

A trend in current workplace planning is the more dynamic use of space, as seen for example in Activity Based Workplace (ABV) models. With such dynamic building usage ventilation capacity can become a problem. For every space ventilation has to be dimensioned for the maximum load scenario leading to significant costs (or inadequate ventilation). The ability to rapidly exchange air volumes between several spaces – diverting ventilation capacity from low occupancy zones to high occupancy zones – has the potential to reduce this problem, as the building ventilation systems can be designed for loads closer to the mean rather than the peak.

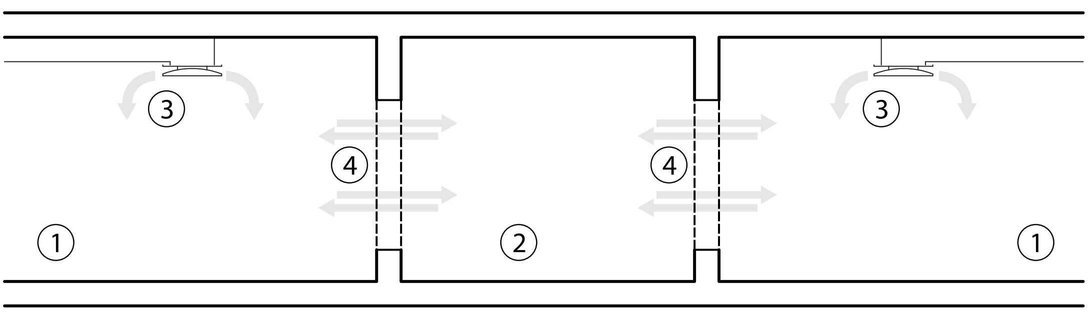


Figure 7.6: Interior ventilation wall. (1): Continuous use room. (2): Occasional use room. (3): Conventional ventilation system. (4): Activated flux ventilation wall.

An internal wall could act as a selective boundary between rooms, connecting ventilation zones across separations which still provide visual and acoustic barriers[3]. Figure 7.6 illustrates how such a structure would allow a space such as a meeting room to be indirectly ventilated through the surrounding spaces which in turn are ventilated through conventional means. The partition wall should be designed to incorporate a reticulated channel network and an internal oscillation activator as shown in figure 7.3c.

7.3.5 Humidity buffering

In chapter three was outlined how current research is investigating the incorporation of humidity buffering into building elements, particularly through the use of adobe clays which have the ability to clamp moisture levels around RH intervals which are beneficial to buildings and occupants. It was demonstrated that those solutions are effective, but require significant surface exposure of raw adobe surfaces and in order to achieve the best effects fans are used to increase the exchange of moisture between the air and solids. Even in the case of using such techniques the buffering is only effective at longer time scales, and hourly or even daily variations are not achievable.

The activated flux structures described in this chapter have the ability achieve a significant increase of the moisture exchange rates without relying on fans, and can therefore enable more efficient and responsive moisture buffering, likely down to hourly time scales. In addition, as the transient mass transfer is able to penetrate tortuous channels and folds, the absorbing surfaces can me located internally in the walls, while the outer surfaces, which are exposed to the building occupants, can be coated with glazing or paint without inhibiting the moisture absorption. This is a problem which has been difficult to address in current research where even a thin cellulose coating was demonstrated to significantly impede moisture exchange rates, and exposed adobe tends to erode and cause contamination.

7.3.6 Indirect evaporative cooling through activated flux

In chapter 3 was described how evaporation from the surface of building components can be utilised to reduce the temperature of the air and solid where the evaporation takes place. This was also tested in chapter 6, where significant evaporation and corresponding temperature drop was observed during a transient flow across the tested panels. With the ability to activate a significant flow of water vapour out of a solid through AFS, significant evaporative cooling effect can be achieved without resorting to static flow across open pools of water, as is described in literature. This enables such systems to be integrated into the building envelope with significantly less severe design constraints.

The most simple implementation is to combine a system for water transport into a transient ventilation panel, which would act through direct evaporative cooling to lower the temperature of the incoming air. Such a system is primarily suited for dry, warm climates. The significant drawback here is the availability and potential ecological impact of the water consumption. A potentially more broadly useful implementation is through indirect evaporative cooling. This can be used to cool the building's structural mass which in turn reduces the internal temperature, without increasing the internal humidity levels.

[3]The acoustic performance of AFS boundaries are not yet established, and would need further research. It is likely, however, that the geometry (Ingard 1967; Godbold et al. 2008) or material/surface of the wall can be manipulated to reduce sound penetration if needed.

7.4 Conclusions on architectural applications

The architectural implementations discussed here show how the mechanisms for transient mass transfer can be used in a a number of architectural scenarios. These range from transient ventilation systems which enable a mass transfer across the building envelope with zero-net bulk flow, to more complex solutions where the fluid flow is exploited as a carrier of energy or matter in and out of the solids and the building interior.

In the case of ventilation across the building envelope it is possible to exploit the ambient wind energy, even if this is turbulent and unsteady, in order to create fully passive systems. It is also possible, and most likely desirable in the majority of cases, to complement this with an oscillation driven component which can be selectively activated in cases of low wind or increased capacity demand. Such a solution maximises the utilisation of ambient wind energy, while giving the greatest control potential. The benefits of such a system have been discussed, and include energy efficiency, a potentially draught-free interior environment, minimising presence the moving parts, the option to condition the incoming air, and potential experiential qualities of such a semi-permeable wall.

The potential drawback of the system lies in the inability to use centralised heat recovery. Because of this, it has been suggested that implementation is carefully considered in relation to the local climate and use context. In some scenarios this may involve using the transient ventilation panels as part of a double skin, or as secondary spaces which are only used in certain times or for certain activities (such as conservatories). It has also been shown that one of the greater potentials for such a ventilation system is in climates with large diurnal temperature variations, where the wall itself can be used as a heat store to achieve complete thermal buffering over 24 hour cycles. This makes the TVP particularly suited for warmer climates.

The capacity to facilitate energy (heat) and matter (moisture) exchange between solids and surrounding fluids holds potential both as a mean for conditioning the incoming ventilation air and to create more complex devices. As has been shown in the literature review, there is a need to develop systems which can increase the flux in and out of high-performance materials such as PCMs, in order to best exploit the capacity the material properties. The advantage of the transient flows is that they are capable of generating high fluxes in and out of complex geometries, where the high tortuosity and surface area ratios result in limitations on cross flows. This also provides a mechanism where the active surfaces of such materials can be hidden from view with only small openings in the finish surfaces. These can then be finished in impermeable ways with sealing paints or glazes, facilitating their use in architectural constructions.

The fundamental idea behind the methods of using ambient energy to regulate building climates relies on the controllability of the flows of heat and water into and out of the building, so that favourable conditions which appear transiently can be captured and disproportionately affect the building interior. For this to be effective, it is necessary to have a relatively large variability of external condition, and the larger the variability the greater the potential benefits. In addition, it is beneficial if outdoor temperatures vary in a way that at least one extreme is crossing the ideal indoor temperature, e.g. during the cool morning hours in a hot climate. Finally, abundant sources of energy such as solar radiation or wind is exploitable, for for direct heating and cooling, but also for indirect effects such as evaporative cooling.

Many such complex devises which utilise ambient energy to condition internal spaces have been described in literature, but are rarely used in architecture because they may be unreliable, slow, or simply inefficient by contemporary standards. The transient mechanisms discussed here provide tools that on the one hand can increase the controllability of these systems, and on the other, can increase their capacity by maximising fluxes in high surface masses and exploit the full potential of advanced materials. In addition, many such systems are reliant on large masses and contact surfaces, and therefore impose severe constraints on the building design. The ability to use complex channels in building solids, and to create discriminatory flows without relying on mechanical valves and separate pipes, provides a mean for integrating functions into building components that serve other purposes.

As the transient mixing is inefficient over very large distances, it is most likely preferable to create hybrid systems which utilise cross flow mechanisms for long distance flows. This way both types of mechanism can be used to their greatest strength, and potential functional bottlenecks can be avoided.

Chapter 8

Discussion

[A]n architecture in which the boundaries between what is interior and what is exterior are blurred, an architecture that avoids the normative distinctions of "inside" and "outside." While the conceptual boundaries of these topological geometries are intriguing, their inherent, conceptual qualities are often difficult to truly manifest tectonically [...] The transparent and solid boundaries of the shelter, which a house must provide, often work against the seamless continuities and erasure of inside/outside dichotomy imbued within the Möbius strip.

– Branko Kolarevic[1]

8.1 Introduction

This chapter provides a reflection on the methods and limitations of the conducted studies, and discusses the wider implications of the findings and the proposed architectural applications. This includes the compatibility of the proposed mechanisms with current building practice, and a reflection of the use of biological systems as models for architecture, both in a specific sense with regards to the termites studied here and in more general terms.

The idea of a mediating, and partially permeable, building envelope goes against much current thinking in the prevailing building paradigm, where the hermetic seal is considered ideal. The hermetic seal, and the associated maximised heat resistance, is of course a product of the need to reduce the energy consumption and maintain stable interior temperatures. This causes some complications for the permeable envelope suggestions presented previously, and which can lead

[1] (Kolarevic 2003, p.13)

to heat loss. But, as I will argue, there are ways around this, and the contradiction is not as large as could be assumed at a fist glance. Second, I will suggest that there are more dynamic ways of viewing the dwelling climate, where place, season and activity can affect the local interior climate in direct ways, and where the suggested mechanisms and application scenarios could be helpful and beneficial. In combination with the constructibility of the relevant geometries, and the potential uncertainties and complexities of the flow behaviour, these issues pose some challenges in any commercial implementation.

However, the other big topic is what “deeply integrated functionality” means in a wider design concept and how to best exploit this. The studies of the termite mound sample, the egress complex, have turned out a number interesting and potentially useful effects and mechanisms. These mechanisms most certainly play a role in the mound physiology, but they are also a part of a much more complex whole. Isolating a sub-component may give useful findings, but further studies of the mound can open up a much larger field of interconnected mechanisms. In addition to this is the fact that even among macrotermites, *M. michaelseni* is but one species, and other species use different mounds and different strategies of mass transfer which utilise geometry and material in different ways.

Considered together, this can build a picture of an architectural paradigm where functionality, materialised in a combination of geometry, material, environment and ’work’ (termite activity in the colony, likely electric actuators in a building), act to generate and control a complex system of flows within the building and the building envelope. Such a vision requires a design process which takes into account the interdependence of these functions, and which is a departure from a reductionist process as we are used to in contemporary design.

8.2 Research method and limitations of this thesis

Horace Lamb, an English applied mathematician, famously expressed in 1932 the following statement (Goldstein 1969): “I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic.” In many ways he was right, and turbulence is still today one of the least understood areas of science. While the Navier-Stokes equations which rule turbulent behaviour have been known since the early 19th century, it is first with the beginning of computational fluid dynamics that we have been able to (somewhat frequently) predict their outcome in complex, real scenarios, and even today such computations require massive computing power and a solid experience with the short-cuts used in the software simulations (Moin and Kim 1997).

In this context it may seem foolish to attempt to build a thesis in architectural engineering around previously unknown mechanisms of transient turbulence. My motivations for doing so, in spite of the obvious challenges which stem both from the limits of my own knowledge and experience, and from the complexity of the subject, is that I believe that we are at a point of convergence, where theoretical concepts of physiology, physics, and computer science are applicable to the more pragmatic applied sciences. Engineers and architects have started to adopt data-driven approaches to design, which allow them to engage with complex quantitative phenomena that were previously far out of reach (Carpo 2014).

The approach of the experiments undertaken here was therefore one of optimistic transdisciplinarity, and to some extent *naive induction* with all its pitfalls (Chalmers 1982). The conducted experiments have been numerous and explorative. In retrospect many of them were trivial or based on false assumptions and have ultimately not been included, but as the work progressed it was possible to start building an understanding for what was going on, that allowed for a gradual establishment of solid hypotheses and experimental procedures. This process of discovery means that the experimental variation is rather large, and there is likely a need to gather more rigorous quantitative data for the purpose of a scientific theory of the transient mass transfer. But this has not been the guiding ambition of the thesis. Instead the goal has been to establish how these mechanisms could be utilised functionally in architectural contexts and to open up possibilities for further investigations. What I do hope has been achieved is on the one hand to provoke experimentalists, both mathematicians and physiologists, to investigate the interaction of geometry and transient flow at an architectural scale, and to formulate testable hypotheses, and on the other to motivate engineers to develop products and processes based on transient and turbulent flow which can be tested at a functional scale. Both of these ambitions require a more narrow scope than what has been possible within this thesis, but I hope that the conclusions from these studies have proven the potential fruitfulness of such further studies.

8.2.1 Certainty of predictions

There are a number of uncertainties within the phenomena and systems explored. Most significantly, the issues of scaling are largely untested, particularly considering the large sizes of buildings relative to the tested panels. This is true at the building component level as well as the scale of the networks. In the case of the former, it would be expected that the net flows based on mixing would follow Frick's law, and be inversely proportional to the distance. This would mean that the transient flows are not well suited to act over long distances, and would be best located to the envelope (or at least to the boundary across which it mediates). Some of the results indicate that the scaling is less dependent on distance than Frick's law would suggest, however. It is not fully clear why this is, but it may be that the increased node count of the network topology in the tested scenarios partly compensates for the increase in distance.

In addition, the scale of the channels in the network have not been greatly varied in the testing, and the specific relationship between activation frequencies and amplitudes on the one hand, and edge length, channel diameter, and branching patterns on the other remains to be discovered. It has been shown that increased edge length of the network increases the minimum threshold for effective amplitude, but it remains unclear to what extent this can be compensated by an increase in frequency, and also to what extent frequency thresholds are dependent on edge length. The number of experiments required to establish the relationship between these numerous parameters grows quickly out of hand without a solid mathematical theory to guide them, and this requires a mathematician rather than an engineer. At the same time a more specific exploration with a clearly defined application could narrow down this parameter search, and allow for a successful engineering approach in full scale experimentation of building components.

The magnitude of the mass transfer has been relatively well established at a lower amplitude range, and there appear to be no reasons to doubt that this would be achievable in full scale applications. The upper limit is however unknown. Theoretically, there is no reason there would be an upper limit, but it is more likely to be a case of diminishing returns, where increasing the energy input results in only minor gains in mass transfer rates, or where other side effects such as noise become a problem. Similarly, it has not been established what the energy input required for the activated transient flow is. The low-power nature of the experiments suggests that the requirements are well within the feasible for the beneficial effects which are obtained, and the tests conducted using natural wind demonstrate that the energy available in ambient wind is sufficient for obtaining significant effects. Beyond these positive signs, the same caveats apply to the energy demands as to the specific scaling and geometry dependencies, and both a mathematical model of the demonstrated flows and full scale testing would provide further information and certainty.

8.3 Transient ventilation in current building practice

The systems proposed in the previous chapter all require significant advances in fabrication and design capabilities: to manufacture such pieces using readily available construction technology may be prohibitively expensive or even impossible. However, as has been argued in chapter two, a new fabrication and construction paradigm is emerging in the industry which has the potential to change the equation, making intricate complexity of form feasible and economically sustainable. This challenge of fabrication however, is not of particular interest in the research question, and I will leave the issue of complex fabrication as a presupposition. There are other potential issues with the integration of such systems in current building practice however, and in this section I will discuss these challenges and what they may imply for the potential implementation of transient ventilation strategies, with an emphasis on section 6.1, *Natural ventilation through distributed permeability in building envelopes*, as this is where the most likely conflicts or differences of approach will arise. The discussion starts at the contemporary trend towards increased building insulation and airtightness, and what this implies for transient ventilation and vice versa. This leads to a challenge of modernist concepts of the building envelope and indoor environment as a binary separation of 'inside' and 'outside'. I will then address the perceived lack of predictability in the type of systems which are proposed in this thesis, and how those issues can be resolved.

8.3.1 Heat conservation and building airtightness

An increasingly important property of the building envelope is to reduce heat loss from the internal environment. This has historically tended to be of greatest concern for colder climates, but as comfort standards are increasing and air conditioning becomes economically accessible to more people in warmer climates, the trend is spreading. This is particularly important in light of the global need to reduce reliance on fossil fuels and overall energy consumption. In regions which have had lower levels of insulation in the past, this is a change which is most easily achieved through adding insulation over past standards. In Northern Europe and similar regions however, increased insulation faces diminishing returns and more attention is given to building airtightness and heat recovery in ventilation air flows. This is well exemplified in Passivhaus standards, which stipulate very high levels of airtightness as well as insulation, but is also increasingly found in national building regulations across Europe (Cotterell and Dadeby 2012).

In order to minimise heat loss, a number of strategies are utilised. The first is to reduce the conductive heat loss through the envelope. This is done by decreasing the average conductivity of the barrier separating inside from outside, and can be achieved by increasing the thickness of the envelope, using materials with lower conductivity (insulating materials), reducing cold bridging (i.e. small, local connections with high conductivity such as beams protruding all the way from slabs to façade), and decreasing air movements within the internal wall spaces. The second is to couple ventilation with heat recovery, either through the use of heat exchangers between inlet and outlet air, or by recovering the heated outlet air in the building heating system through the use of heat pumps. The third and final strategy is to reduce unwanted leakage of air through the envelope, as the associated heat loss cannot be recaptured through a heat recovery system. An envelope section with a distributed permeability for transient ventilation can cause problems for all these strategies. If not designed with great care, the permeable envelope section lead to thinner walls and more cold bridges, and the turbulent flow in the channels may disturb the performance of an insulator. However, the greatest problem with such a solution in a cold climate is the inability to exploit any form of central heat recovery[2], and such limitations are likely to exclude these types of ventilation solutions from uses where the ventilated environment needs to be significantly warmer than the surrounding environment, such as residential buildings in northern Europe during winter months. As has been noted in the previous chapter however, a high building airtightness is not in itself problematic for distributed permeability ventilation, rather such constructions are a pre-condition for the effective operation of such a system.

Activated flux structures, which do not necessarily form a direct connection between indoor and outdoor, and where the flow can effectively be turned on or off according to conditions, are generally less problematic. However, some care must still be taken to ensure that such structures do not interfere with the thermal performance of the building envelope.

In light of these limitations one may be tempted to rule out the use of distributed transient ventilation for any cold climates. This, it can be argued, would be an over-simplified response and it may be more productive to question our functional definition and use of the building envelope.

8.3.2 The building envelope as a mediating boundary

With the advancement of the modernist era came a greater focus on the building as a functional machine, something meant to separate its inhabitants from the surrounding environment, perceived as harsh and unwanted. Addington (2009) describes the change from a building envelope which mediates between the inside and the outside to the envelope as a container of the body's environment, decoupled from any surrounding conditions. This change was brought about largely by the development of HVAC systems in the earlier half of the 20th century, described by contemporary architects such as Le Corbusier and Frank Lloyd Wright as the emergence of the 'hermetic' envelope, which went from a boundary of exchange to a boundary of discontinuity (Addington 2009). As the energy crisis of the 1970's set off a necessity to reduce energy consumption (which was combined with the new demands of comfort stemming from a widespread affluent lifestyle), the focus fell on the envelope as a barrier, and an accelerating trend of perfecting the barrier in order to prevent not just physical but energetic flows between the two.

Our perception and design of the indoor environment is based on the assumption that a "perfect environment" exists, typically defined as the conditions where we don't notice it at all. A common model for thermal comfort is Predicted Mean Vote (PMV) developed by Fanger (1970), and which defines thermal comfort as "those conditions where 80% of occupants do not experience discomfort." While some recognition exists that such perfect conditions vary depending on person and activity, for example by guidelines of varying temperatures in bedrooms and living rooms etc., the ideal of a static, continuous environment nevertheless prevails.

[2]It may be possible to design some form of local, convection driven, heat exchanger cells in the system (see for example Olsson (2012)), but such an undertaking is beyond the scope of this thesis.

Contrast this model with the mediating boundary envelopes of past, vernacular architecture, where the living space inside the walls breathed, negotiated, changed with the seasons and the use. During winter the shutters were closed, the family gathered around the hearth of the home and animals brought in. Activities still took place in the building's colder parts or outside, but then with thick clothes and physical activities to stay warm. In spring, the building dissolved, allowing greater space and freedom responding to the dynamic nature around it. Or to the termites' nests and mounds, so deeply integrated with their inhabitants that the definition of what is the *organism* becomes blurred. The homoeostatic zone, for us easily defined by the skin of our bodies, extends beyond the termite individual, incorporating the fungus they cultivate as well as the mounds they build - in itself a regulatory homoeostatic organ of the termite super-organism (Turner 2000b). This homoeostatic zone changes with the seasons and with the activity of the termites: as the rains fall and the termites procreate and their activity is at its peak, the zone of homoeostasis extends throughout the mound, whereas in the dry season when the termites retreat to their nest and their metabolic rate decreases, the homoeostatic zone shrinks down to below the mound, leaving the vast structure looking deserted and lifeless, waiting for the next burst of activity.

Our perceived comfort is not static but dynamic. It responds to our mood and activity, changing with the minutes, hours, seasons. The conditions which are required for maintaining the health of our body are much more tolerant than those that determine our comfort, and located to different parts of our body (Addington 2009). How we perceive temperature is not only determined by the surrounding temperature, but by the movement of air through wind or buoyancy, by the relative humidity, and by radiant exchange. This opens up a host of potentials for the building to interact in a dynamic way with its inhabitants through variation (spatial and temporal, over various scales) and direct interaction.

8.3.3 Trends toward adaptable comfort conditions

As has been suggested in the previous section, the static view of comfort expressed by (common interpretations of) Fanger is currently evolving. Studies conducted by for example Nicol and Humphreys (2002) and Dear and Brager (1998) demonstrate that our thermal comfort is dependent on contextual factors, and that our preferred comfort temperatures are affected by behavioural adjustment as well as psychological adaptation. The latter was found to be true particularly in naturally ventilated buildings, where subjects demonstrate a significantly increased tolerance to temperature variation than HVAC buildings.

Baker and Standeven (1996) suggests that the simplified approach to comfort criteria which fails to take into account behavioural and psychological adaptation often leads to an unnecessary inclusions of electric cooling in early design stage analyses. This is particularly likely as free-running buildings[3] exhibit greater unpredictability and variation than actively cooled or heated buildings, a type of condition where adaptation is a particularly effective strategy.

In response to this developing view of adaptive comfort models, regulation is evolving. Nicol and Pagliano (2007) outlines how the European Standard (CEN EN 15251 2007) has been written to allow for a greater variability in indoor climate, concluding that "[t]his will mean that buildings

[3]Here I use *free-running buildings* to describe a building which is not consuming external energy for the purpose of heating or cooling. External energy in this case excludes ambient sources, such as wind or sun (although some cases, such as on-building solar cells are border-line, but would likely fall outside of the free-dunning definition.) Thus a particular building can be partially or fully free-running depending on its instantaneous operation during different times and cycles.

can be designed which are both comfortable and can make full use of passive, low energy cooling and heating technologies."

These changes will facilitate the implementation of the strategies outlined in this thesis, as they decrease the risk associated with such strategies and remove regulatory hurdles. Conversely, the need to improve existing passive strategies for comfort regulation will likely increase as a result of more widespread adoption of free-running buildings, creating increased incentive for innovation in both design and fabrication.

An architecture of continuous spatial variability

Within this conversation lies the possibility to challenge the binary definition of the building's inside in relation to its surrounding. The boundary can be dissolved into a selective and variable membrane, allowing the inside to merge with its environment across a continuous range of conditions which vary spatially as well as temporally. The conservatory, almost ubiquitous in the perception of English dwellings, is the most primitive of such variations, but demonstrates some of the potential of responsive variability in architecture. The role of transient ventilation is then perhaps not always to replace the conventional HVAC system, but to expand the repertoire of the building designer in order to enable her to create such variability, which in turn will increase the opportunities for behavioural adaptation and lead to increased comfort of the building inhabitants and users.

8.3.4 Buildability in current and future technology

The structures demonstrated in the previous chapter exhibit a significant geometric complexity, and the experiments conducted indicate that the prevalence of a multitude of reticulated and interconnected channels, as well as their relative small dimensions are of critical importance for the optimum performance of the system. However, there is little indication that a standardised, repeating geometry would not function at optimum from a mass transfer perspective. This facilitates faster and cheaper fabrication options, particularly in the near-term.

Various casting techniques are attractive as they could enable relatively inexpensive fabrication of large quantities of such structures. However, the complications involved with the channel networks would likely require some variant of lost form-work, which increases the complexity and cost of such options. If attempted, processes similar to those outlined by Gardiner and Janssen (2014) would likely provide an attractive option. For full scale experiments and prototyping a subtractive process where the panels are fabricated from a series of sections, each containing only straight perforations, seems the most practical. A sectioning process could also make casting significantly less expensive, and this may be the most attractive alternative for commercial production in the near term.

Ultimately, however, the possibilities of the strategies outlined here are best exploited in a mass customised scenario. This would enable a functional integration of the kind which is discussed later in this chapter, and a much more sophisticated adaptation to micro-context. In this scenario the more suitable technology is additive fabrication, which (at least in theory) carries no cost penalty for high geometric complexity and full customisability. As outlined by Soar and Andreen (2012), the cost of additive fabrication has to come down significantly for this to be feasible, but several research efforts are under way which attempt to bridge the scale and cost gap which currently exists.

These efforts are currently focused on large scale concrete printing, but it is likely that other materials can provide a better match for the demands of the building industry. Particularly, various clays have properties that make them attractive for employment in a functionally integrated building envelope. These benefits range from the absence of aggregates which are troublesome for a nozzle and its variable rheology, to the varied and particular properties of clay as a finished material. As will be discussed below, unburned clay can combine with elaborate geometric configurations in ways which mediate some of its typically troublesome behaviour when exposed to rain or other moisture, and exploit the nano-scale properties of a "live" material. Burned clay – ceramics – similarly has advantageous properties ranging from its extraordinary durability and hardness to moisture absorption and transportation characteristics. In addition, glazing of ceramics provides a further method to manipulate the material behaviour, particularly with the regards to interaction with water, and this can be selectively applied.

8.4 The problem of reductionism or the simplification of biological processes

Any attempt to describe or understand morphogenetic processes in nature with the intent of applying similar processes or functions in engineering contexts risks oversimplification or misinterpretation. To a large extent this is because of the fundamental differences between design in human contexts on the one side and the biological processes of evolution and morphogenesis on the other. In human contexts it is impossible to escape intent and purpose, which imposes a top down perspective and a need for predictability and control. These concepts are alien to biological systems which have no designer and no purpose in themselves, but which simply are, or with a different perspective of time scale, emerge.

Reductionism[4] implies that the complex whole can be described as the sum of its parts, and is the *modus operandi* of architectural engineering, as it allows the buildings structural integrity to be considered in isolation from its thermal conductivity, its representational expression, or any other aspect of the building. Because of this physical building components can be designed and made independently and the building process can be separated into sections, each one of which can be planned and carried out independently. Such a model is however inadequate to describe biological morphogenesis, partly because functions are deeply integrated and intertwined within various structures and organs, and partly because the formation of the structures and organs themselves is interdependent and simultaneous.

This does not make a reductionist approach to biomimetics irrelevant, as much is still to be learned from the functions and processes of biological organisms which can be fully implemented and applied in an engineering context. Indeed, this is the premise of the previous chapters, and in reality emergent and reductionist approaches are not mutually exclusive. However, in order to build a better understanding for how mechanisms such as those discussed in this thesis interact and act together emergently, further research into the termite mounds and the interaction of material, geometry and physiological function is necessary.

[4] Or specifically *causal reductionism*, described in the Interdisciplinary Encyclopaedia of Religion and Science as the ability to reduce a complex system to the sum of its parts so that "the causes acting on the whole are simply the sum of the effects of the individual causalities of the parts".

8.4.1 Further investigation of the transient models of *M. michaelseni* mound ventilation

A significant portion of the literature review of this thesis has been dedicated to the mass transfer mechanisms of the mounds of *M. michaelseni* termites. As is evident from the review, the understanding of these mechanisms is tentative, and while there is significant evidence that the mass transfer is at least partly driven by complex transient flows across a range of frequencies. The experiments which have been done in the previous chapters provide a significant, and in some ways unexpected, clue to some of the workings of the investigated mounds, but the investigation is limited to a small component of the full mound geometry, and the results can not be put in their full physiological context. The unexpected nature of the results come from the frequency range at which these have been discovered, in order of 10-100 Hz. The frequencies which have been recorded in the actual mounds by Turner (2001) are significantly lower, in the range of 20 mHz (see figures 3.11 and 3.13). This suggests that the mechanisms involved are perhaps even more diverse than previously assumed.

The findings of chapter 6 demonstrate that the simple exposure of the egress complex to external wind, while it demonstrably leads to mass transfer across the EC, is not sufficient to fully exploit the geometry's ability to convert oscillatory motion to large scale convection and mass transfer. While it is possible that the geometry-dependent effects documented in chapters 4 and 5 are not active in the mound proper, this appear an unlikely coincidence. It is then perhaps more likely that the rest of the mound geometry is in some way involved in generating oscillations which lead to mixing and turbulent convection in the EC. A possible mechanism for this is that the mound and nest in its entirety generates oscillations when it interacts with the wind or some other energy source, perhaps through resonance. A closed cylinder of four metres of length, which is in the range of the dimensions of the surface conduits of the mound (see chapter 2), has a resonant frequency of approximately 20 Hz. These oscillations would permeate the mound and collect energy from a large range of frequencies. As this frequency is very close to the frequencies which induced the strongest response in the egress complex, the energy could then be translated to turbulence in the specific location of the mound which is the egress complex, significantly enhancing the mixing of air across this outer barrier.

From an architectural perspective, this is a quite attractive hypothesis as it may be possible to fairly easily replicate such effects in a building[5]. However, no tests have been made as to how this may work, and the hypothetical presence of such resonance effects in the nest have not yet been conclusively studied, and the possibility has been left out of the previous applications chapter.

It is also not known what the purpose of the EC mixing is in the mound. The most obvious hypothesis is that is allows for transfer of respiratory gasses between the upper mound structure and the surrounding air. However, an alternative hypothesis relates instead to the water content of the mud in the building process during the mounds expansionary phases. The mud used for construction by the termites comes from the bottom of the mound and is wet. Once the moist mud is deposited, it may be beneficial to lower the water content as this would make the built structures more stable. As has been shown, the types of turbulent flows which are cased in these systems are very effective at causing evaporation, taking the moisture away from the building material. At the same time, this would cause a local zone of elevated relative humidity in connection to the

[5] 20 Hz is at the lower hearing threshold of the human ear, meaning that such a system would be minimally intrusive.

build zone which may be a stigmergic trigger that reinforces and preserves the termites' building behaviour.

Serially linked mass transfer mechanisms

The mass transfer mechanism observed in the experiments reported in this thesis are all acting at a small scale, around 10^{-1} meters. While it may well be possible to extend the effect over larger distances, the size of the egress complex precludes this in the mound. The termite nest, where most of the metabolic activity takes place, is located at a distance several meters away from the air surrounding the mound and from the egress complex. This indicates that other mechanisms are operating within the mound as well, which is also suggested by Turner and Soar (2008) in their proposed model. Another important aspect of such a multi-phase system is the potential ability to maintain the internal homoeostasis with the help of increased control of different flows which is due to the variability of the mechanisms, as a single phase system only enables linear regulation.

A deeper understanding of these various mechanisms and their interdependence may open up further potential for building systems and may extend the range of climates and scenarios where transient ventilation can be applied.

8.4.2 *Odontotermes obesus* – steady flow mound ventilation

As fascinating and full of potential the mounds of the termite species *M. michaelseni* are, they are not the one perfect solution for ventilation – even for termite mounds – and the principles employed are the response to a very specific evolutionary niche. This is well illustrated by the mounds of a different species of macrotermites, *Odontotermes obesus*. These termites are native to southern India, and like *M. michaelseni* they cultivate *Termitomyces* in subterranean nests which are surrounded by a mound structure playing an important role in the respiratory gas exchange of the colony. These mounds have been documented during a research expedition, and some of the documentation can be found in Appendix A.

O. obesus mounds do not have an egress complex as in the mounds studied in Namibia, and the internal tunnel structure is quite different as well as the mound shape. Rather than the cone-like shape of the *M. michaelseni* mounds, these mounds have a number of fins, or buttresses protruding from the mound centre, forming a star-like shape in plan. In these fins are found circular passages starting from the base of a chimney on top of the nest, rising upwards and looping through the fin back to the base of the nest. In these spaces has been recorded a slow, continuous flow which appears to be driven primarily by the buoyant forces stemming from heat caused by the solar irradiation of the fins (King, Ocko and Mahadevan 2014). This steady flow transports respiratory gasses between the nest and the fins, where an exchange appears to take place across the porous walls of the fins.

The nature of the mound outermost walls appears to be a driving difference between the two ventilation strategies. The *O. obesus* walls are of an even thickness of approximately 10 mm and of a shell-like structure, whereas the walls of *M. michaelseni* mounds are thicker and more solid but with a large perforation of tunnels, particularly in the egress complex where the tunnels perforate the outer surface. One could speculate that the nature of the Namibian soil provides a less strong building material, forcing the wall thickness to dimensions which make diffusion through the wall insufficient, thereby driving the emergence of the egress complex. Whatever the reason, the ventilation strategies are markedly different, which highlights the need for architectural applications of these types of complex ventilation systems to be adapted to the particular building.

Structural properties of a thin, breathing clay skin

The thin shell of the mounds provides an interesting contrast to human adobe, or unfired clay, constructions. Such buildings are typically constructed from thick walls and cannot survive external exposure in wet climates. Historically in Europe such buildings have been surface coated with a lime mortar to prevent erosion and loss of compressive strength due to wet conditions (Morton 2008). The mound shell in contrast is very thin and lasts through the wet season in south-western India without any external coating, and while maintaining sufficient porosity to enable respiratory exchange, at least between rainfalls.

It may well be that the composition of the mound clays is better than the clay used in the construction of dwellings, the termites add a cellulose component to the clay while mixing it in their mouth parts, but a likely more significant factor is the physical structuring of the shell. The inside of the wall is covered by pits which are 5 mm in depth or about half the thickness of the wall. The pits are placed in an equidistant triangular pattern over the whole inside with about 10 mm centre-to-centre distance. The pitting is thought to have a dual functionality. The first is to enhance the permeability of the wall while causing the least possible loss of structural integrity, in short an optimisation of the permeability to strength relationship. The second functionality is more speculative, but suggests that the careful manipulation of the shell geometry makes the material more resistance to the degenerative forces of external humidity. The strength of the clay material diminishes as its moisture content increases (Lawrence et al. 2009), so in order to prevent the degradation of the outer surface, its moisture content has to be kept as low as possible. The moisture content depends on two factors, the flux of water in and out of the material. The exterior face will during rainfall be wet, and water will flow into the material. The inside however, will face the stable internal environment which acts as a humidity sink thanks to the gentle circulation and large buffering mass. As is shown in the appendix, the pitting of the inner surface increases the internal surface area with 40% relative to the external surface area, and decreases the average distance from all points within the wall to the inner surface with 50%. The effect of the pitting is therefore to increase the flow of water out of the wall, to keep the moisture content of the clay lower and it is therefore able to retain more strength. This effect is further enhanced by the properties of the clay material, which swells when wet thereby limiting the transport of water from the wet (outer) side into the material.

If such a model could be tested and shown to work, it could provide intriguing possibilities for complex building skins where the performance of the envelope could be significantly enhanced over the material properties in themselves through the interaction of shape and material, or macro- and micro-structures. The purpose of including this speculation in this thesis is to illustrate the wide range of potential applications of geometry-influenced local flows of air and water through the structure, and how these interact with material effects and properties.

8.4.3 Temporal adaptation and variability

Any attempt to model engineering on biological systems is likely to come up the challenge of static versus dynamic systems. The termite mounds, like the tissue of organisms, are never static constructs but are continually altered and repaired. This is superficially about a constant repair (and this aspect plays into the mounds' ability to withstand rain damage even if is not the exclusive reason for this), but on a more profound level about the dynamic nature of homoeostasis, or biological adaptability (defined by Turner (2000b) as "maintaining a state in the face of changing conditions"). The termite mound is not static, but it is regulated by the work expended by the termites to maintain the balance of fluxes. These fluxes are of variable nature, from the flux of soil from the mound to the ground, caused by erosion, and the flux of soil from the ground to the mound, caused by the termites[6]; or the flux of respiratory gasses which are consumed (or produced) within the nest, but replaced though the mounds' ability to harness wind energy. As the colony grows, so does its metabolic demands, and the flux of soil from the ground is increased leading to a bigger mound which is able to capture more wind, thus compensating for the increasing demands (Turner 2008). These changes are not only steady and linear, but the homoeostatic zone within the mound is changing over the seasons as the metabolic activity alters in response to changing resources (such as in the dry season), or the activities and thus demands of the colony (such as the increased metabolism during the time the alates fly).

The assumption that a human-built dwelling must mimic these changes is erroneous (after all, our rhythms, demands, and methods are distinctly dissimilar to those of the termites even if we implement biomimetic termite-inspired mechanisms in a building), but we as humans and building inhabitants also have cycles (internal as well as external) which the building should respond to, and too simplistic an implementation of such inherently adaptable mechanisms poses the risk of missing the potential.

Of more immediate concern is perhaps the superficial implementation relating to the durability and maintenance of such a building. Even if is feasible to fabricate the complex geometries required, do the geometries inhibit maintenance? And looking at the resilient but thin envelopes of *O. obesus*, the strategy for maintaining the integrity of the skin appears to be dependent on minimising erosion as opposed to eliminating it. Any implementation of a similar method must take this into account by adding to or altering the strategy, or by allowing for a regular maintenance.

Electrical sensors and actuators provide one obvious way of addressing this need for temporal variability. To a certain extent such mechanisms are very likely to be embedded in any building envelope (and particularly in the case of activated transient fluxes of the kind described in the previous chapter, as these require mechanical activation). Whether this is an appropriate strategy for long term adaptation of physical structures – such as the tunnel networks here envisioned – remains to be seen. An alternative route may be in accepting – and designing for – the limited life-span of building components. In an additive fabrication scenario any arbitrary part of a building envelope can be removed and reprinted, either because of changing demands or because of decay and erosion. A building material, such as the gypsum-based materials proposed by Soar and Andreen (2012), which is sustainably recyclable from both an economical and ecological perspective could open up the door for such strategies.

8.5 Conclusions

The constructional challenges involved in making the kinds of applications which have been presented in the previous chapter are not insignificant, but also clearly within the reach of current industry capabilities. Fabrication could likely be accomplished using relatively conventional formative and subtractive technologies, even though an additive process promises to offer greater ability to customise or adapt to local micro-contexts, or to integrate multiple functions in single building components.

[6] This flux is significant: up to several hundred kilo every year.

It is likely that the ventilation strategies which have been proposed are more suited for warmer climates than what is found in Northern Europe, but that implementations in such colder environments could also be viable if the building envelope is adapted to be more dynamic and flexible, offering a less binary distinction between inside and outside, and where the buildings internal zone could change with seasons and use. Systems which are based on activated flows are more likely to be viable in colder climates, as these can be selectively turned on and off, and can be used to redistribute heat or humidity loads either internally or between the building interior and exterior, thereby reducing peak loads and decreasing the energy requirements for HVAC.

It has been shown that the potential of using geometry to influence flows of air, moisture and heat within a building is significant, and that the mechanisms developed in this thesis are but a small part of the range of mechanisms which could be established through further research. The understanding of the workings of termite mounds is still very limited and much remains to be discovered and learned. Further research also involves developing the initial application suggestions presented in this thesis to realised building components to reveal how they act in full scale and within a specific design scenario.

While material has been shown to have no influence on the emergence of transient mass transfer as described in the thesis, materials are still highly significant in any application as they will interact with the generated flows through their properties: thermal capacity, moisture adsorption or desorption, etcetera. These points are particularly illustrated by the brief study of *O. obesus*, where the mound acts in different ways and utilised different mechanisms to accomplish similar end results in a different context.

It has also been suggested that the key to a successful business model based on additive fabrication is to provide a large number of functional effects integrated in a single component. Because of the interacting nature of these effects, this would require (or at least benefit from) a departure from reductionist design processes. Such a non-reductionist process could likely be modelled on biological processes of morphogenesis[7], whereby organisms get their shape or form. The advantage of developmental processes or morphogenesis lies in their ability to manage immense complexity, far beyond what is possible in conventional, top down design paradigms, and to achieve a predictable end function in the face of varying and unpredictable circumstances. Biological systems, relative to engineered ones, exhibit deep integration of shape(s) and function(s). An integrated design process, modelled on developmental biology, provides a mean to generate such integrated structures, where a single continuous envelope can provide a multitude of functions without being sectioned and segmented, physically or conceptually. From the perspective of the structures and devices discussed in this thesis, such an integration could be of significant benefit.

Research into such design models is increasingly prevalent among architectural researchers (Hensel and Menges 2006; Oxman and Oxman 2010; Bentley and Kumar 2003; Menges 2012b; Andrasek and Andreen 2015). If the mechanisms described here can be taken into account into such models of *digital morphogenesis*, it is likely to greatly extend the possibilities of what can be done though an additively fabricated architecture.

[7] in *Wikipedia*: **Morphogenesis** (from the Greek *morphê* shape and *genesis* creation, literally, "beginning of the shape") is the biological process that causes an organism to develop its shape.

Chapter 9

Conclusion

> *[T]his kind of synthetic landscape offers resilience and redundancy of transient boundaries, with an increased ability for interweaving contingent agencies. The role of those boundaries is no longer to enclose space, but rather to form tissue for osmotic exchange. What could be called data materialization is opening up the potential for architecture to finally resonate with the complexity of ecology.*
>
> – Alisa Andrasek[1]

9.1 Introduction

The ambition of this thesis has been to explore how termites manipulate and exploit the geometry of the mounds surrounding their colonies in order to create an internal environment suitable for their physiological needs, and to demonstrate that it is feasible to use similar mechanisms to regulate the internal climate of buildings through complex manipulations of the internal geometries of the building envelope and structure.

The work presented here has shown how the mounds of *M. michealseni* termites can interact with transient wind in order to generate mixing across a barrier in a manner previously not described in literature, providing further clues to the workings of the termite mound physiology and the fluid dynamic interactions around complex 3-dimensional shapes. It has been described how the geometric parameters can be manipulated in order to control how and when these phenomena occur, and how they may be utilised in engineering applications as the effects can be quantified and predicted.

[1] (Andrasek 2012)

The thesis proposes how these described mechanisms can be utilised in architectural applications in order to improve the potential performance of buildings by increasing comfort and reducing the buildings ecological footprint. Based on the current state of the art of the construction industry, it is likely that fabrication and design capabilities that enable the complex geometries required will emerge within a near future, and somewhat limited implementations may be fully possible to build using today's technology and economic context. The ability to create deep integration of functional performance in a non-discrete building envelope can provide added value to the fabricated products in ways which justify the large scale implementation of additive fabrication technologies in the construction industry.

9.2 Mechanism for transient mass transfer

It has been proposed in literature (Turner 2001; Turner and Soar 2008) that transient mass transfer mechanisms are present in the mounds of *M. michaelseni*, and that these mass transfer mechanisms are not dependent on steady cross flow mechanisms as has been previously assumed. Further, the suggestion has been that these mass transfer effects arise because of the interaction between the specific geometry of the termite mound, a reticulated network of variable edge length, and the distribution of ambient wind energy across a range of frequencies. However, these phenomena have not been described in specific terms, and the evidence for such mechanisms is indirect.

In this thesis has been presented evidence for such mechanisms, demonstrating that transient mass transfer in and out of dead zones is possible. This was shown in chapter four, where the egress complex was connected to a sealed chamber and exposed to oscillations of a low amplitude (5 mm), significantly smaller than than the thickness of the barrier (50-100 mm), and smaller than the edge length of the tunnel network (8-30 mm). Using a tracer gas, it was shown that the mass transfer rates were increased between one and two orders of magnitude over the unperturbed system, achieving a equivalent flow of 0.01 l/s. Doubling the amplitude of the oscillations increased the mass transfer rates by a factor of four, suggesting that the rate is proportional to the square of the amplitude, but with the caveat that there is a minimum threshold in amplitude below which the turbulence is not generated, and the mass transfer is much smaller.

It was further shown that the phenomenon only arose in response to oscillation frequencies between 10 and 100 Hz, with the strongest peak around 20-30 Hz. It is likely that the thresholds for frequency and amplitude are interdependent as they both affect velocity. A hypothesis was proposed, that the emergence of turbulence is determined by the combination of velocity (or potentially acceleration) and the ratio of displacement amplitude to edge length. While this hypothesis needs to be developed into a mathematical relationship and tested, which is beyond the scope of the thesis, the demonstrated interdependency of geometry and oscillation properties supports the suggestion by Turner and Soar (2008) that the various parts of the termite mound, whose geometry is spatially variable, derives work from different frequency ranges found in the ambient wind, and that this allows the mound to generate discriminatory[2] mass transfer.

[2]Discriminatory mass transfer refers to spatially variable, selective mass transfers, such as the evaporative panting of dogs. Turner and Soar (2008) writes: "Panting cools a dog by elevating the rate of evaporative mass loss from the mouth and lungs, driven by an increased lung ventilation. This poses a physiological quandary: how to increase water vapour flux without simultaneously increasing carbon dioxide flux, which could cause severe upsets of the body's acid-base balance. The quandary is resolved by the lung's impedance. Driving the lungs at the resonant frequency of the thoracic cage increases the lung's impedance. Ventilation therefore preferentially enhances

Furthermore, the mound (EC) geometry was tested together with a number of similar geometries, where the level of reticulation of the tunnel network was varied. It was found that the reticulation was critical for achieving the mass transfer rates documented above, and that the mass transfer rates increased with increasing levels of reticulation, at least up to the amount found in the EC itself. The lowest levels of mass transfer was recorded in the straight channels where no reticulation or branching existed.

9.2.1 Nature of flow

The flow patterns were documented in chapter four through the use of smoke and planar laser, from which still video and images were taken. These showed the emergence of large scale turbulence near the openings of the EC and in the test chamber. Because of the opacity of the EC panels, the experiments of chapter five were carried out in a 2-dimensional test set-up which allowed for the visual documentation of the flow patterns in the reticulated channels. These tests retained the same spatial scale, but used water as the medium rather than air, where a strong dye could be injected. In order to maintain dynamic similarity between the two systems, the frequency of oscillations was adjusted to 2-6 Hz which resulted in similar Reynolds and Womersley numbers. The results of this visualisation confirmed the emergence of turbulence within and in connections to the reticulated tunnels. In both cases this turbulence emerged at Reynolds numbers of around 10-100, which should normally correspond to laminar flow (White and Corfield 2006). As the straight channels produced less or no turbulence at the same Reynolds numbers, it can be concluded that the reticulated geometry is critical for the conversion of laminar oscillations to turbulent flow, which was also the case for the mass transfer rates. It is not clear exactly how this conversion takes place, but geometric irregularities are generally associated with an increased tendency for turbulence, and it may be that some form of synthetic jetting phenomenon occurs around the many orifices in the tunnels. As the emergence of turbulence is determined by frequency, amplitude and the edge length of the network, it is likely that the phenomenon is dependent on both the velocity of the fluid, and the distance travelled in each oscillation cycle relative to the edge length.

It was also seen in the visualisations that the dye concentrations in the channels was uniform, which indicates a lack of laminar boundary layer. This was contrasted to the clear boundary layer which formed in a steady flow, and which limited the contact of the external fluids with the tunnel surfaces. As has been described in the literature review, this is the expected result from turbulent flow, as fluid and any carried particles move in every direction and not just parallel to the average flow direction, and is significant for the potential architectural application of the mechanisms, as described below.

9.2.2 Natural wind as transient driver

The tested panels were exposed to external turbulent wind, both generated from a small fan and by placing the panels in natural outdoor wind conditions. It was thereby established that a similar level of mass transfer could be achieved by exposing the outer surface of the egress complex and the alternative panels to a turbulent air flow, while the inner chamber remained sealed, thus forming a dead-zone (Braun et al. 2009) where external static flows would not typically penetrate. A significant finding in these experiments was that, contrary to the oscillating flow conditions, the topology of the channels did not affect the mass transfer rates. This indicates that the topology is

evaporation from the upper respiratory passages. The lung's elevated impedance to these high frequencies leaves flux at the deeper, mixed regime level unchanged."

involved in the translation of oscillating flows to turbulent flows, as the turbulence in this case of forced upon the system from external sources. A deeper reticulated panel was tested which showed a decrease of mass transfer rates which was roughly proportional to the inverse of the thickness. It is expected that a thicker panel would further reduce the rate of mass transfer as the external wind gets depleted of energy as it penetrates deeper, relative to the oscillation induced turbulence, which is generated internally across the full width of the panel. It is also expected that the unreticulated geometries would exhibit a faster drop off of transfer rate with increasing thickness as the longer pipes would require greater spatial pressure variation to penetrate the single pipes.

As the termite mound is not exposed to any known oscillation source other than the wind it remains unclear how the described mechanisms are operating in the mound. It may be that other aspects of the mound's complex network of passages and channels is involved in the conversion of wind to regular transience in the frequency ranges that correspond to the 20-30 Hz shown to be most effective. One potential mechanisms for this is resonance in the surface conduits which are directly connected to the egress complex. This is somewhat supported by the fact that the results in chapter four indicate that the optimum frequencies were affected by the resonant properties of the system as a whole, which was shown when the back chamber tube was varied in length. However, this is limited to speculation, and further research would be needed to understand the greater picture of the mound physiology, and how the different mechanisms work together.

9.3 Regulation and control

In chapter four was shown that the mass transfer rates were greatest for a range of frequencies, and that manipulating those away from an optimum led to a decrease of the transfer rates. It was also shown that the flow rates are likely proportional to the square of the amplitude, allowing for an easy regulation of the achieved rates. In the following 2-dimensional tests the parameters were extended and these effects were correlated to adjustments of the geometric properties. From those experiments can be concluded that a threshold exists for both frequency and amplitude, under which significant turbulence does not arise and where the resulting mass transfer is low. It was also shown here that this threshold was found in different places for varying edge length of the tunnel network.

This provides a mechanism which can be used to achieve spatial variability of the mass transfer in a variable network of tunnels, by manipulating the amplitude and frequency of the oscillations, without any alterations of the physical shape of the tunnels. To fully understand the relationship between geometric and oscillation parameters, further mapping and testing is required, and likely also a more robust theoretical explanation of the flow mechanisms.

9.4 Architectural significance

Mass transfer through convection is, together with the conductive transfer of heat and internal heat generation, the primary process through which the building climate can be regulated. It is a source of undesirable effects, such as leakage of heat through the building envelope, as well as a number of desirable effects. These include ventilation, which manages respiratory gasses and keeps pollution low, and several mechanisms which actively move heat and water around within the building envelope. These spatial and temporal displacements can significantly reduce the need for externally supplied energy to maintain the stable interior climate, as has been shown in the literature review.

In contemporary building engineering, these flows are almost exclusively designed using steady cross flows, where a lot of effort is put into maintaining laminar flows. The reason for this is that turbulence is regarded as unpredictable, uncontrollable and a source of energy loss within a steady flow. What has been shown in this thesis is that turbulent and transient flows can be generated with a high level of precision and control, and that they can be an efficient mechanism for mass transfer in the right conditions. The nature of turbulence gives these flows a number of advantages. These include the ability to ventilate dead zones which wouldn't be accessible for cross flows (which require dual openings at opposite sides); the strong advantage of turbulent boundary layers over laminar ones with regards to promoting mass and heat exchange between solids and fluids; the demonstrated controllability of flows in discrete spatial regions as opposed to the continuous flows required in static flows; and the ability of turbulent flows to reach pockets of air which are resulting from complex geometries and high surface area passages.

The ability to create discriminatory flows without physical separation (either through selective oscillation activation, or through the use of oscillation properties tuned to specific geometric features), and to use these mechanisms in narrow, complex spaces is an advantage when creating designs where functionalities are integrated in the building envelope or structure.

9.4.1 Needs identified in literature

In the literature describing current research into passive and natural methods for regulating building climates, much emphasis is placed on material developments and discrete systems. The former is exemplified by development of materials with high thermal mass (phase change materials) or moisture buffering properties (clays, end-grain wood). A common challenge in using these materials is to match the mass or thermal transfer rates with the high capacity of the materials themselves, so that the full material potential can be exploited, as is shown by Zhang et al. (2007). It is similarly evident in the data presented by Padfield and Jensen (2011), which show that in practice only 3-20% of the moisture buffer capacity of common moisture buffering materials can be accessed in a 24 hour cycle. Efforts to mitigate these material inadequacies are addressed by for example Lamberg and Sirén (2003) and Padfield and Jensen (2011), through geometric manipulation of the materials in the form of fins, perforations or other regular shapes which increase surface area. However, these are combined by either passive flows or fan-driven cross-flows which rapidly decrease in effect as the surface area increases and the irregularities become more significant.

In these scenarios, the transient flows which have been described in this thesis are particularly well suited both because of their ability to penetrate narrow, tortuous spaces, and because of the turbulent boundary layer which promotes heat and mass exchange with the buffering masses.

The discrete nature of many of the systems being developed in current literature is questioned by Zhang et al. (2007), which calls for more research in how high-tech materials (such as PCM) can be integrated into the building envelope, and how to work actively with thermal storage solutions by linking them to ambient energy. A similar call for functional integration is expressed by architects and engineers such as Lim et al. (2012), Menges (2012a), and Hensel (2013); the transient mechanisms demonstrated here can provide an important enabling role for the development of such systems.

9.4.2 Proposed implementation scenarios

In this thesis has been proposed a number of scenarios where the transient mass transfer mechanisms can be implemented to help regulate building climates. These scenarios include natural and assisted ventilation, heat and moisture buffering, and conditioning of indoor air.

Using transient flow mechanisms as described here for ventilation purposes requires a semi-permeable building envelope, where fresh air is taken in across a relatively large envelope area. Such a solution would bring a number of benefits: the interior space could remain draught free as the transient mixing does not increase air velocity; an experiential connection between the interior and exterior would be created; the incoming air could be easily conditioned; and the system can easily be passively driven by wind, resorting to electric drivers only when there is need. However, this solution would expose the building to potential heat looses, so it is not always an ideal solution from an energy perspective. However, as has been discussed in the previous chapter, there is a growing body of evidence for a greater than previously believed capacity for thermal adaptation, both behavioural and psychological. This is particularly true in free-running buildings, and suggests a rich area for different implementations of transient mass transfer mechanisms and systems in such buildings.

Further, the problem of thermal leakage could be mediated by using the permeability selectively. In a northern climate this may imply a double skin envelope solution which can open or close the wall depending on the external condition, or by the creation of semi-indoor spaces which are used differently during different seasons, weather conditions, and activities. In a warmer climate the problem would be smaller, and particularly in climates with large diurnal variation. Here it has been shown that the transient ventilation wall could act as a diurnal buffer, achieving enough thermal storage capacity and transfer to maintain a stable temperature across the 24 hour cycle.

Such transient ventilation could also potentially be used for internal redistribution of air, decreasing the peak ventilation capacity needed in buildings where asymmetric use is common, for example many contemporary offices.

As is perhaps suggested above, heat and moisture buffering is likely where the greatest potential for the transient mass transfer can be found. This is exemplified in the suggestion for asymmetric thermal storage in the structural mass of the building. By creating several intertwined tunnel networks in a single mass, it is possible to link this thermal mass to both the outside and the inside of the building envelope, and selectively activate the convective heat transfer between the thermal mass, the outside of the building, and the interior (at different times). Thus can a solution be created where the most advantageous hours of the diurnal cycle can be used to charge the thermal mass with coolth or heat from the outside, which can then be distributed to the building interior in a uniform or selective manner. It would then be possible to achieve a internal average temperature which differs significantly from the outdoor average temperature, replacing heating or cooling through external energy sources. Use of advanced materials, such as phase change waxes or salts, could greatly enhance this ability.

Furthermore, similar solutions could be used to buffer humidity or to create cooling through evaporation, all of which would benefit from the demonstrated properties of the turbulent flows. In all situations, the potential of the system to affect the internal climate is affected by the usable ambient energy available. This means that large temperature variations, particularly in a diurnal or faster cycle, is advantageous, as is energy in the form of direct solar radiation or wind. Solar radiation can be a source of heat, but can also quicken evaporation, and is therefore a potential source of coolth as well and can work to dissipate humidity.

9.5 Towards an adaptive building envelope

The transient mechanisms described in this thesis provide for a number of opportunities to exploit complex geometries. In conventional construction such geometries have been prohibitively expensive to fabricate, but with the emergence of additive fabrication processes for construction scales, is is potentially possible to achieve these complexities at reasonable cost. It has been argued here that in order to justify the investment in additive fabrication, a maximum of added value must be created by the fabrication processes. The likely source of such added value is to integrate multiple performative functions into the built structures themselves.

The contribution of this thesis is not to provide comprehensive solutions, but to build up an understanding for how geometry can be used in combination with turbulent and transient flows to manipulate the building climate and how the building relates to its environment, external as well as internal. Transient flows have been shown to facilitate the use of high surface area ratios which often cause prohibitive limitations for steady and laminar flows, and as they don't build up pressure differentials, they are less dependent on physical separations. Together this provides means to facilitate integration of multiple functions in non-discrete building components of the kind that can be fabricated additively.

It has been shown that such flows can be activated and controlled in a selective, discriminatory way without the use of physically actuated barriers. This is a key point in the ability to achieve integrated multi-functionality at reasonable costs. In combination with locally distributed sensors, such a building could be designed to respond to changing conditions, actively redistributing heat and moisture through the building envelope. Such a construction would be more resilient to damages due to damp, would be optimally suited to exploit micro-climate variations, could minimise heat losses or moisture influx, and could respond to changes in use or context through rapid adaptation without physical alterations of pipes or connections.

From a less technical perspective, the ability to create selectively permeable building envelopes presents challenges to the conventionally perceived binary distinction of indoor and outdoor, suggesting a more dynamic treatment of the boundary between the two. Such a treatment, facilitated by the semi-permeability of the building envelope, may allow architects greater freedom to deliver the type of experiential performativity suggested by Hensel (2013) or Addington (2009).

Many aspects of such dynamic boundaries are commonly found in parts of the world where the reliance on electricity and other heat sources are more limited than in Northern Europe, either due to climate or lack of economic means. It is in these parts that population growth and increasing prosperity are creating many new opportunities, but also the potential for a significant increase in global energy consumption, not least because of new demands on living comfort that is today most likely to be achieved using HVAC installations. Perhaps it is here where the greatest benefits of the technologies described can be achieved. The hotter average temperatures and large ambient energy gradients typically available in many such regions are the types of conditions which an active building envelope can exploit. At the same time, the lack of established centralised construction and energy infrastructures means that new technologies, particularly if they can rely on locally sourced materials, are at a relative competitive advantage. If implemented, it is likely that these mechanisms can be used to improve the performance of passive and low-energy solutions to a level where they are good enough to satisfy the increasing demands for comfort, saving large amounts of CO_2 emissions and creating new human values.

Appendix A

Odontotermes obesus Case Study

A.1 Introduction

The macrotermitae species *Odontotermes obesus* is found on the Indian sub-conteinent, and is a fungus cultivating and mound building termite with many similarities to *M. micheaelseni*, though of smaller size. This appendix outlines a study of these termites' mounds. They are interesting for this thesis mainly because of their differences from *M. michealseni*, as they appear to utilise wholly different mechanisms for mound ventilation. As such, they can expand the 'toolbox' of the engineer seeking to utilise geometry for functional purposes, but they also provide an important reminder that the processes found in *M. michaelseni* mounds are only one possible way of achieving similar purposes.

The ventilation of respiratory gasses in the *O. obesus* mound is accomplished through a a dual mechanism where the exchange of CO_2 and O_2 between the mound and surrounding air is a diffusion process through the relatively thin and porous skin (envelope) of the mound in the buttress-like structures (see figure A.1). This is complemented by a slow and steady circulation of gasses between the nest (shown as (1) and (2) in figure A.2) and the buttresses (shows as (5) in figure A.2). This circulation system has been investigated and described by King, Ocko and Mahadevan (2014), which is in preprint at the time of this publication. The flow is driven by diurnal temperature variations, where the buttresses with their large surface area and relatively low mass rapidly change with ambient atmospheric temperature and solar radiation and the nest remains relatively stable. Thus the direction of the flow is reversed twice over every cycle. Contrary to the termosiphon model proposed by Luscher, external heat sources rather than metabolic heat appear to be the primary energy source.

The velocity of the flow is small, in the range of cm/s, and greatest at night. The lower flows during day time leads to a gradual build up of CO_2 concentrations of around 6% during this time.

A.2 Functional geometry

The mounds have been investigated and described in geometry and function. Figure A.1 shows the external geometry of a number of mounds situated at or adjacent to the National Centre for

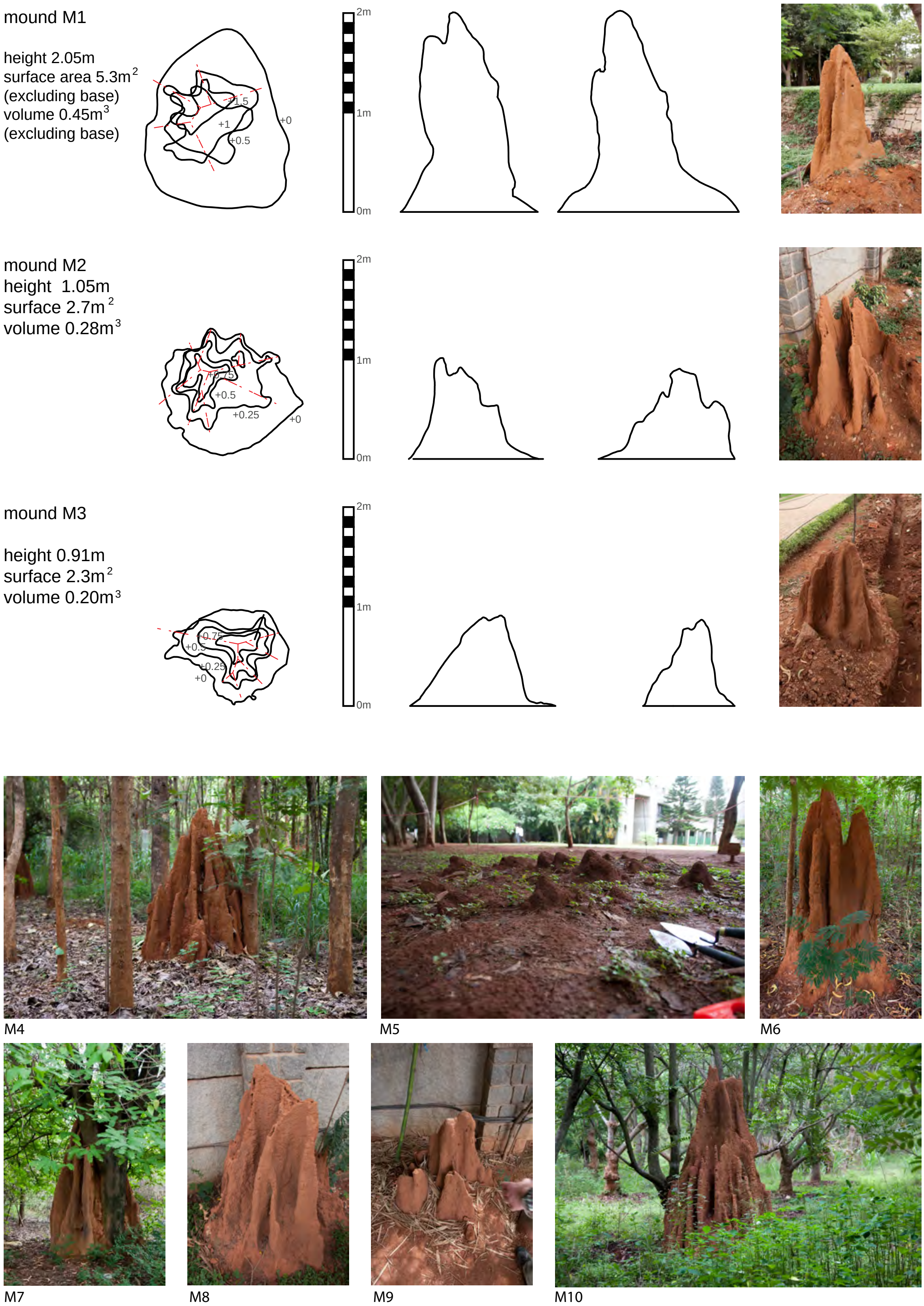


Figure A.1: External geometry of *O. obesus* mounds.

Biological Sciences in Bangalore, India. Three mounds (M1-M3) have been mapped in detail using Microsoft Photosynth software processed in Meshlab and Rhinoceros 3D. The mounds vary in height between only a few centimetres up to about three meters, and all (with the exception of the colony M5 which only had a few moundlets) show a similar flanged geometry, with the mound being flanked by a radial arrangement of buttresses. The three mounds which were mapped in 3D all exhibited a similar ratio of surface area to volume of about 10 m^2 surface per m^3 of volume.

The internal geometry of the mounds is documented and described in figure A.2. The main colony is found in the inner (1) and outer nest (2). These are connected via a central chimney (4) and an interconnected mixing zone (3) to the buttresses (5).

A.2.1 Internal structure of buttresses

In spite of their name and apparent similarity to the buttresses of Gothic architecture, the mound buttresses are not considered to be primarily structural in function, but rather their shape contribute to the circulation and ventilation of respiratory gasses in the mound. The flange-like geometry allows for a large surface-to-volume ratio, which has a dual purpose. On the one had this large surface area allows a larger diffusion of gasses across the envelope, and on the other they function to absorb and release heat to the environment at a rapid pace, thus providing the heat differentials which drive the internal circulation.

The internal structure of these buttresses has been examined and this is documented in figure A.3, a photograph of a single buttress which has been cut in half, and figure A.4 showing an internal gypsum cast of a buttress.

In both of these is evident the significant void space, and the dense and uniform distribution of notches, or blind egress channels, on the inner surface of the envelope. These notches are found in an approximately triangulated grid, where each notch is flanked by six neighbours at an average distance of around 10 mm. The depth of the notches is approximately half the skin thickness, or 5 mm, and the average diameter is 2.3 mm. The notch density on the sampled buttress is 10,000 m^{-2}. This is significantly higher than was noted by Abou-Houly (2010) in the *M. michaelseni* mounds (2,000 m^{-2}). These data are collected in table A.1.

Property	Value	Standard deviation
Skin thickness	8-12 mm	n/a
Average notch depth	5.4 mm	2.4 mm
Average notch diameter	2.3 mm	0.47 mm
Average distance between notches	10.7 mm	3.3 mm
Average number of adjacent notches	5.8	1.5
Notch density	9,500 notches / m^2	n/a
Ratio of branching notches	10% (corresponding to thicker envelope)	n/a
Notch area ratio	4%	n/a

Table A.1: Properties of cast buttress, notches. Data is based on random selection of 15 notches except for notch density, notch area ratio and ratio of branching notches where all notches on one side of buttress were counted.

Of further interest was that approximately one tenth of the egress channels or notches were branched into two separate channels, and these corresponded to the regions where the envelope was slightly thicker. This suggests that the termites can sense the proximity to the outer surface of the envelope, perhaps by gentle increases in airflow, or decreases in CO_2 concentrations.

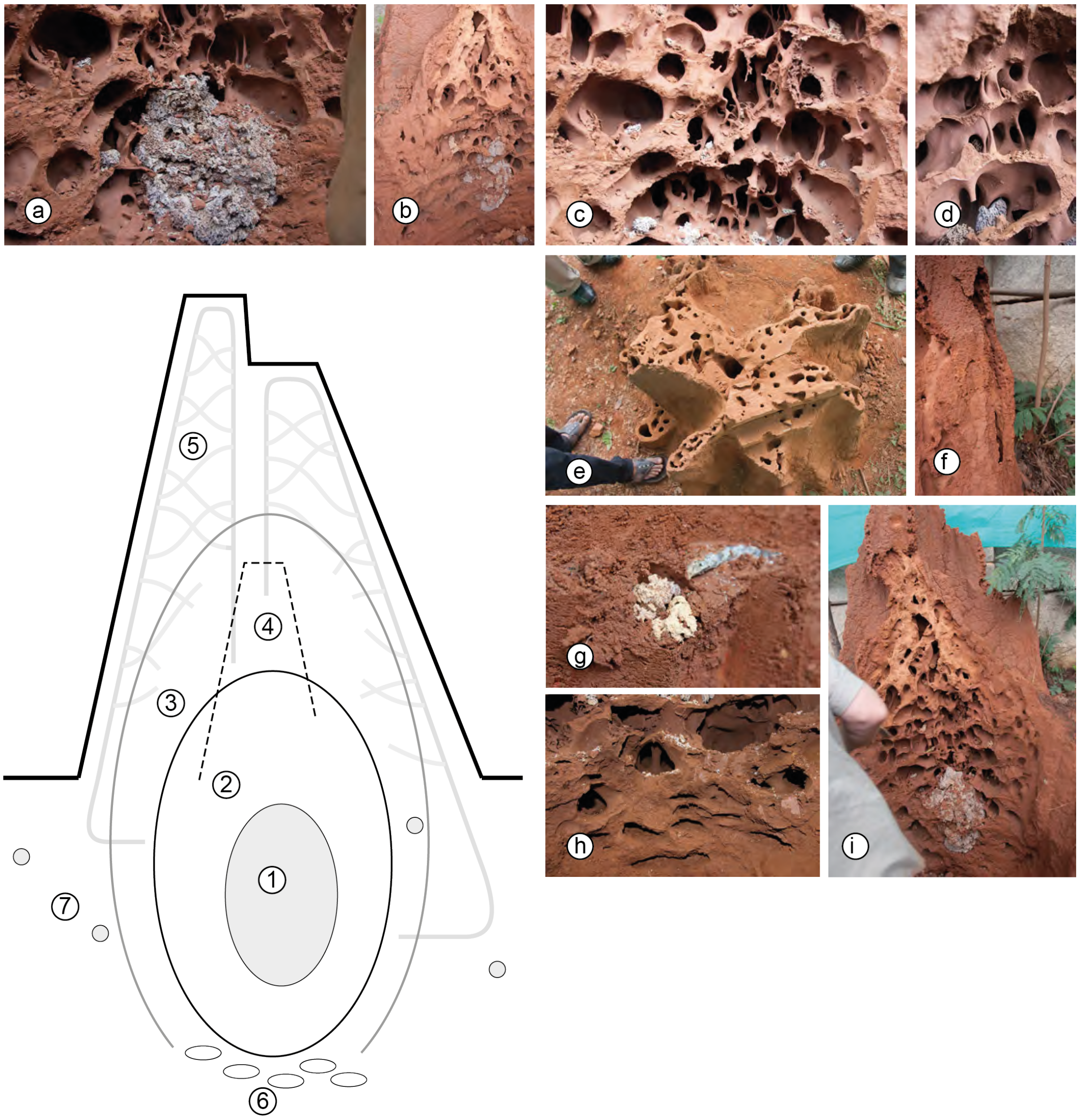


Figure A.2: Mound structure. **1. Inner nest** The inner nest (a,b) is composed of a roughly spherical collection of fungus combs and houses the queen and nymphs. **2. Outer nest** The horizontal, lamellar structure of the outer nest (c,d). **3. Mixing zone** The nest is surrounded by a zone of interconnected channels (i) linking it to the channels in the mound and buttresses, including a small central chimney. **4. Central chimney** The top of the outer nest forms a small central chimney (e, i) which extends up into the mound where it appears to connect to the channels in the buttresses. **5. Buttresses** The mound is composed of a radial arrangement of buttresses (e). The buttresses are hollow by means of a network of interconnected channels, and connect to the central chimney and the outer nest through the mixing zone. **6. Cellar** Underneath the nest is found a simple cellar composed of horizontal chambers (h). **7. Peripheral fungus gardens** Around the nest are found peripheral fungal gardens which are spherical and golf ball-sized, containing a single fungus comb (g). These are connected to the nest through a single, narrow tunnel.

A.2.2 Mound material

The mounds are composed mainly of clays, in a similar composition to the prevailing red soil in the area. Some basic material tests were carried out, establishing a porosity of 30-35% for dry (though not oven dried) material samples. Further tests had been carried out by Tejas Murthy, which showed a 40-40% porosity for oven dried samples, as well as a plastic limit of 16% and an organic content of 5%.

In order to test the material's behaviour in water, a small sample taken from a buttress was suspended in water. After 15 minutes, the sample was retrieved and split in two. Figure A.6 shows the penetration of water into the sample, with a moist region extending about 5 mm from the surface and the wet region extends only about 1 mm into the clay.

A.2.3 Notch jetting

Simulations carried out by Abou-Houly (2010) indicate that the presence of notches in the envelope of the termite mound can significantly increase the permeability to flows of gasses. Simulations indicate that the formation of a jet can be expected at the mouth of the notches when a pressure differential is present between the two sides. In order to test this a simple experiment was set up which mounted the mound envelope sample to a sealed chamber to which a vacuum pump was attached. By using a planar laser and injecting smoke into the test chamber, a visualisation of the internal flows was created. The results of this experiment is shown in figure A.7. In A.7a the pressure on both sides of the sample is equal, and little or no movement is visible in the internal chamber. As the realtive pressure in the chamber is decreased, a jet is formed at the openings of the notches, as predicted by the simulations (A.7b).

A.2.4 Notched envelope properties

By introducing notches to a solid material slab, the properties of the slab are altered. To quantify this, an idealised notched envelope section was created from which data was taken that in turn was compared to the equivalent section without notches. The section used was 10 mm thick, and the notches were distributed in a triangulated pattern in accordance with the data in table A.1.

The inner, notched surface has a 141% of the surface area of the un-notched surface. The volume of the notched section, however, is only decreased 2% in relation to the flat section; in combination with the triangulated distribution this means the loss of structural strength is likely only negligibly decreased. Data from Abou-Houly (2010) suggest that with a lower notch density the flow across the envelope increases 50% (though this is pressure driven flow, the difference is likely smaller for pure diffusion), which would be significantly higher for the 5 times larger density found in this case.

Finally, figure A.8 shows the distance of random points within the volume of the envelope to the inner surface. Introducing the notches significantly decreases the average distance to the inner surface from 5 mm to approximately half this. This may, depending on the nature of the air flow in the inner surface effect the migration rate of water from the mound material to the air on the inside of the envelope.

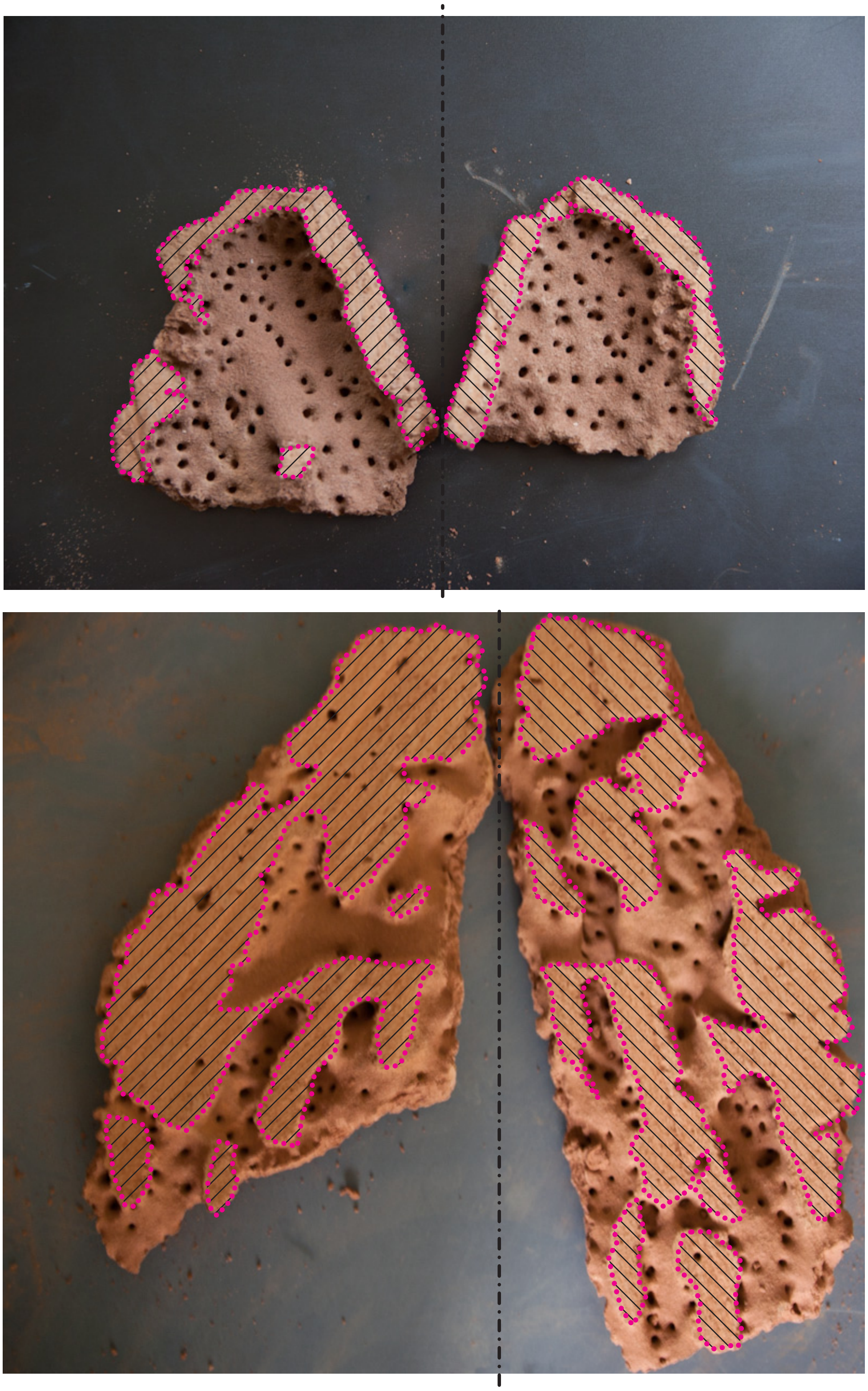


Figure A.3: Internal surface and structure of buttresses.

Figure A.4: Gypsum cast of buttress internal voids.

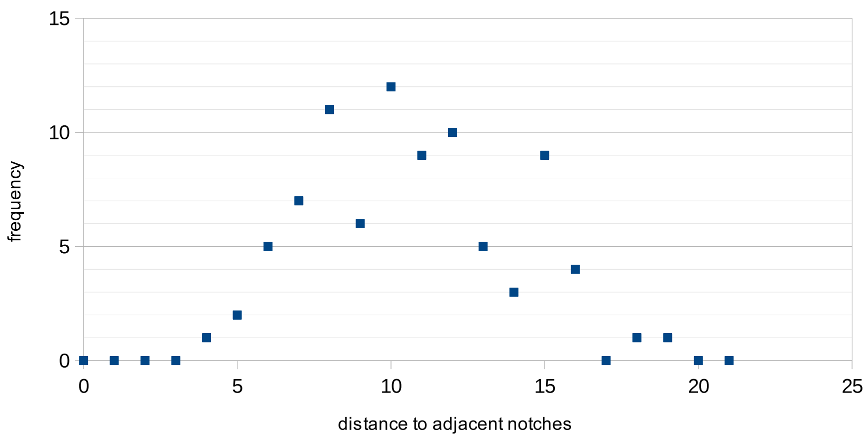


Figure A.5: Frequency of notch-to-notch distance, based on 15 randomly selected notches on cast.

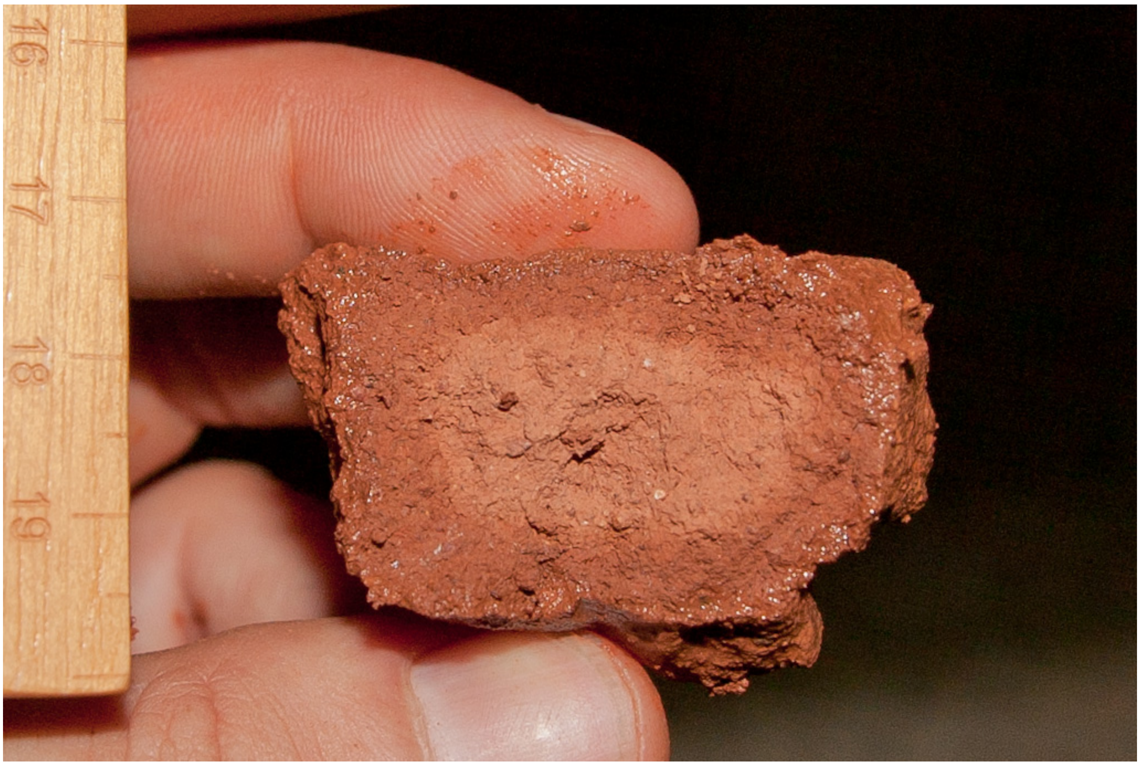
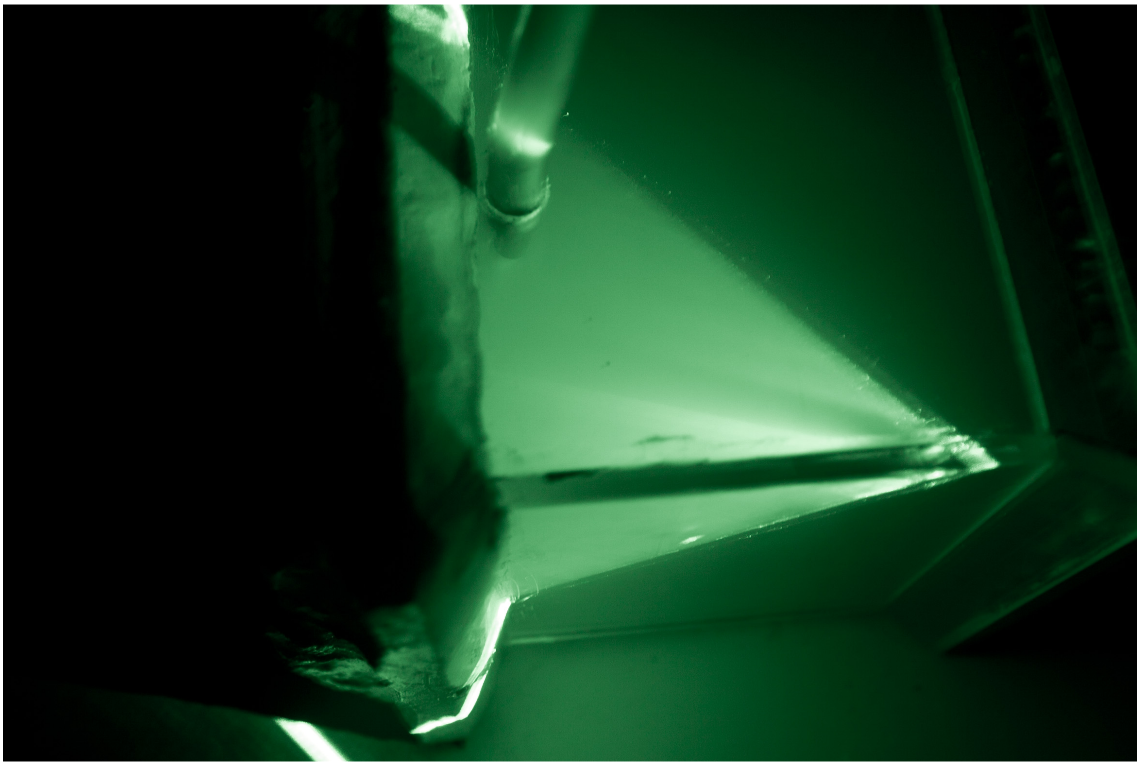
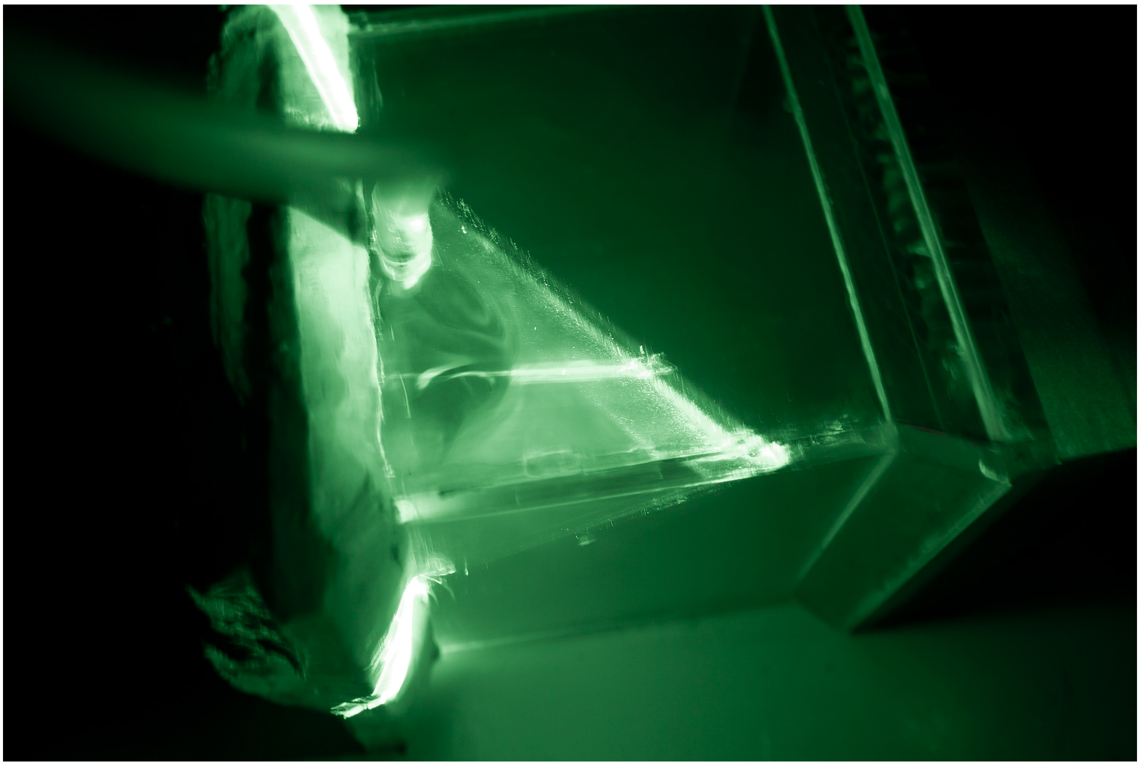


Figure A.6: Material sample of mound envelope. Water penetration after 15 minute suspension in water.



(a) Equal pressure at both sides of envelope sample.



(b) Lower pressure on inside chamber causes flow across envelope sample.

Figure A.7: Visualisation of flow across mound envelope sample, showing jetting effect by notch geometry. Illumination of smoke-filled chamber by planar laser.

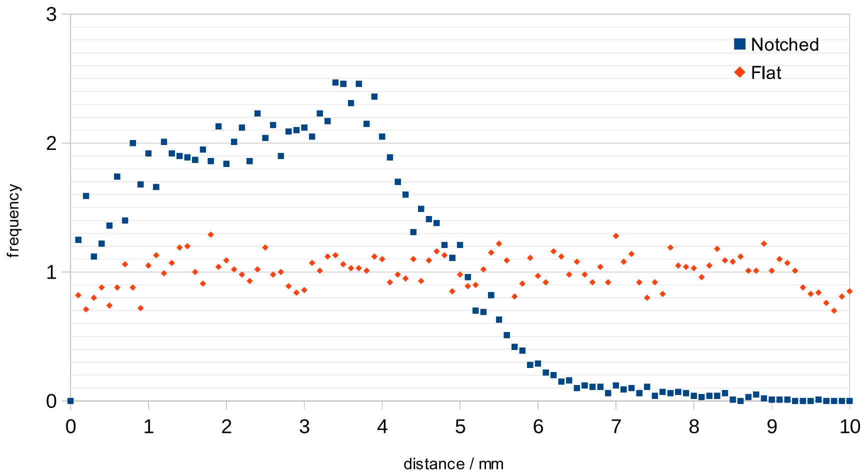


Figure A.8: Internal surface and structure of buttresses.

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